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AUG 79 D R SMITH, J L OSTERHOLZ

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ENGINEERING PUBLICATION NO. 5-79

ASSESSMENT OF FREQUENCY SELECTIVE FADING ON DCS TRANSMISSION SYSTEM PERFORMANCE (REPORT NO. 1)

AUGUST 1979

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ADE 100 356

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DCEC-EP-5-79	2. GOVT ACCESSION NO. AD-A087 994	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Assessment of Frequency Selective Fading on DCS Transmission System Performance. ~~(Report No. 1)~~		5. TYPE OF REPORT & PERIOD COVERED Engineering Publication
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David R. Smith; John L. Osterholz		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Defense Communications Engineering Center, Transmission Engineering Division, R200, 1860 Wiehle Avenue, Reston, VA 22090		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N/A
11. CONTROLLING OFFICE NAME AND ADDRESS Same as #9		12. REPORT DATE August 1979
		13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) N/A		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

A. Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18. SUPPLEMENTARY NOTES

Review relevance 5 years from submission date.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Frequency Selective Fading
Shallow Fades
Digital LOS Transmission
Adaptive Equalization
Computer Simulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Recent reassessments of digital LOS transmission systems indicate that transmission is affected by more than power fading alone. Tests showed that extensive inband amplitude and phase distortion occur during even relatively shallow fades. To facilitate the study of these phenomena, a hybrid computer simulation of the AN/FRC-( ) ( ) DCS Digital Radio was developed, and is described in this EP.

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August 1979

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EXECUTIVE SUMMARY

This publication is the first of a series of engineering reports describing the progress of a study which addresses the effect of frequency selective fading on DCS digital microwave communications. Frequency selective fading has been found to occur on well sited and well engineered (by analog standards) digital radio links and has been the cause of poor error performance on a number of test links as reported by Bell Telephone Laboratories (BTL) and others.

This report presents a model of the selective fading channel in a form so as to make simulation of the channel and subsequent performance analysis tractable. This model differs from other models published to date in that it explicitly relates link parameters such as antenna size, path length, terrain and climate factors to both the magnitude of frequency selectivity in the fading microwave channel and, more importantly to its probability of occurrence. The model provided an estimate of frequency selectivity which is in close agreement with experimental data collected by BTL for a test link within the United States.

This report also describes the major features of a hybrid analog/digital computer simulation which is being designed to model the frequency selective fading channel as well as the major digital radios utilized in the DCS. It is believed that this simulation represents the most detailed and complex simulation of a communications channel attempted to date.

Finally, as this publication reports on an ongoing effort, a program plan governing the overall investigation is presented. This plan describes the analysis and experimental phases of the effort as well as providing a schedule for subsequent reports and major program milestones.

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I. INTRODUCTION

This report is the first of a series of engineering publications. These publications will describe the progress and summarize the results of a study addressing frequency selective fading on DCS LOS transmission system design. This report describes a channel model derived to enable the assessment of frequency selective fading via hybrid computer simulation. The report also describes a hybrid computer simulation of the AN/FRC-( )( ) DCS Digital Radio and briefly discusses those areas of AN/FRC-( )( ) design and performance which can be impacted by frequency selective fading. Subsequent reports will describe the results of the AN/FRC-( )( ) simulated performance tests; the objectives for a LOS propagation/digital link performance test effort; the results of the link test; and an assessment of the impact of frequency selective fading to include assessment of the need for adaptive equalization on DCS links.

II. BACKGROUND

The Defense Communications Engineering Center (DCEC) is responsible for the specification of transmission system performance for all DCS applications, from the U.S. Government-owned and operated systems such as the Digital European Backbone (DEB) project to the 45/90 Mb/s leased digital Washington Area Wideband System (WAWS).

Prior to 1976, digital LOS transmission at rates below 100 Mb/s was widely assumed to be affected only by variations in received signal level. However in 1977, with the initial fielding of digital LOS transmission systems operating at rates appropriate for FCC authorized common carrier use, this assumption was reassessed. This reassessment was initiated by tests performed by Bell Telephone Labs (BTL) and Bell Northern Research (BNR) on LOS radios with 2 bits/cycle modulation techniques, similar to those planned for DCS application. In recent publications (1, 2), BTL and BNR of Canada have disseminated the results of these tests. Both BTL and BNR found that the measured performance fell far short of the expected performance based on the commonly held assumption that bit errors result from power fading alone. The results of these tests implicated extensive inband amplitude and phase distortion which was found to occur even during relatively shallow fades (i.e., frequency selective fading). BNR went further and recommended the use of adaptive channel equalization techniques for digital LOS applications.

In 1976, DCEC also examined the available literature and generally addressed the subject of frequency selective fading in DCEC TR 12-76, DCS Digital Transmission System Performance (3). In TR 12-76, the effects of frequency selective fading were judged to be not serious for the majority of government-owned DCS LOS links, since 70 percent of the links are 30 miles or less in length, are implemented at data rates of 28 Mb/s or less, and occupy RF bandwidths of 14 MHz or less. However, a number of the remaining links are long enough so that current theory suggests frequency selective fading may be a problem on these links and should be reconsidered. In addition, a number of high capacity (45-90 Mb/s) digital LOS systems are being planned to satisfy DCS requirements within the U.S. To support these plans, DCEC must develop transmission system performance specifications. The specifications must consider the effects of frequency selective fading to insure that practical system performance objectives are established which can be achieved at a reasonable cost.

Recently, the development of adaptive equalization for digital troposcatter communications was successfully concluded. The equalizer developed for troposcatter provides a convenient vehicle for assessing whether adaptive equalization can mitigate frequency selective fading in digital LOS systems. Coincidently, the adaptive equalizer developed by Bell Northern Research (BNR) for possible application to LOS radios, is closely related to the digital troposcatter equalizer. Additionally, Motorola in 1973 developed a baseband adaptive equalizer utilizing decision directed adaptation and successfully implemented it on actual LOS links during digital imagery tests. However, mitigation of radio equipment degradation rather than frequency selective fading was the prime objective of the Motorola tests.

BTL and BNR experimental results indicate that the use of diversity transmission may still be required to achieve acceptable fade outage rates even with adaptive equalization. The DCS digital radio, AN/FRC-( )( ), utilizes a dual diversity selection combiner with a diversity combining algorithm developed at DCEC for DCS application. The algorithm can be responsive to inband frequency selective distortion and will, in principle, provide the required diversity improvement. However, the actual improvement realized is strongly influenced by the implementation of the performance monitors used by this algorithm. Thus, an evaluation of the offset signal quality monitor as implemented in the AN/FCC-( )( ) digital radio under frequency selective fading conditions is appropriate.

III. HYBRID SIMULATION OF THE DCS DIGITAL LOS RADIO

1. DCS RADIO MODULATION TECHNIQUE

The DCS Radio (AN/FRC-( )( )) utilizes different modulation techniques to achieve the two performance levels required by the governing specification (4). Quadrature Phase Shift Keying (QPSK) modulation is utilized to meet Level I performance which is achieved at a nominal RF spectrum efficiency of 1.0 bit/cycle, while Quadrature Partial Response (QPR) modulation is utilized to achieve Level II performance at a required RF spectrum efficiency of nominally 2.0 bits/cycle. A more detailed description of the AN/FRC-( )( ) radio and the other equipment procured under the U.S. Army managed Digital Radio and Multiplex Acquisition (DRAMA) Program is presented by J. Mensch (6).

Because of the assumed greater sensitivity of QPR which uses multilevel amplitude and phase modulation of a CW carrier to amplitude and phase distortion relative to QPSK, this study will concentrate on QPR performance assessments. Additionally, since the QPR configuration of the AN/FRC-( )( ) will be the most commonly employed in the DCS, concentration on QPR is even more appropriate.

QPR, as a modulation technique, can be viewed as a derivative of QPSK with special pulse shaping. As seen in Figure 1, instead of binary pulses (i.e., rectangular or raised cosine pulses) as transmitted in QPSK, a QPR modulator generates pulses that through special filtering are not binary but three level. The three level QPR baseband pulse stream is used to phase modulate a carrier in a manner identical to that accomplished with QPSK. However, unlike QPSK, the transmitted QPR signal has both amplitude and phase modulation. The special filter used to generate the 3 level QPR baseband is called a Partial Response Filter (PRF) after Kretzmer (7). The theoretical PRF frequency characteristic and impulse response used in the AN/FRC-( )( ) radio are shown in Figure 2(a). In Figure 2(b), the RF signal constellations of QPSK and QPR are presented to show the degree of amplitude modulation used in generating the QPR transmitted waveform.

Detection of the QPR waveform is similar to that of QPSK up to the baseband level. At baseband, the demodulated QPR signal has three distinct levels (in the absense of noise); it can be readily regenerated by using amplitude slicers referenced to the noise-free baseband levels, followed by a three-level-to-binary decoder which digitally removes the intersymbol interference caused by the composite PRF characteristic. In most practical implementations, the PRF characteristic is apportioned evenly between the transmitter and the distant end receivers. In addition, differential encoding/decoding is normally employed to resolve the 180 degree phase ambiguity inherent in four phase modulated signals.

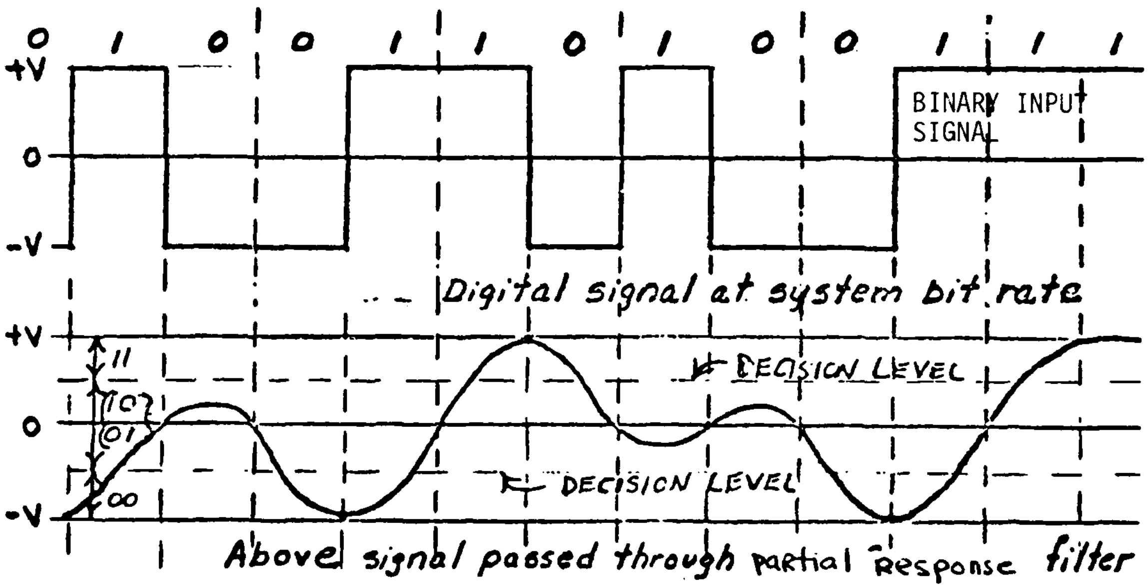
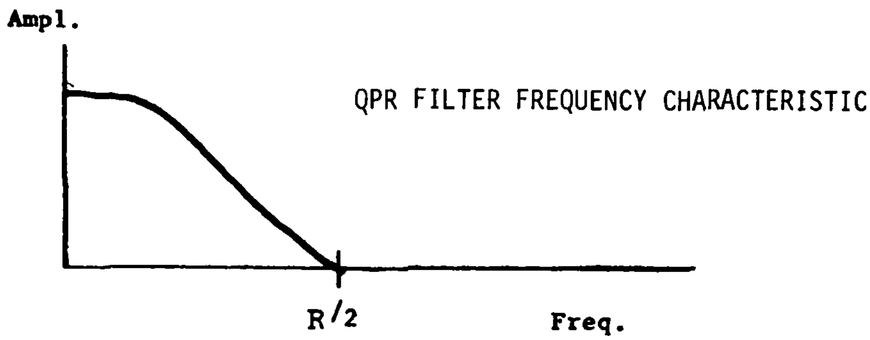
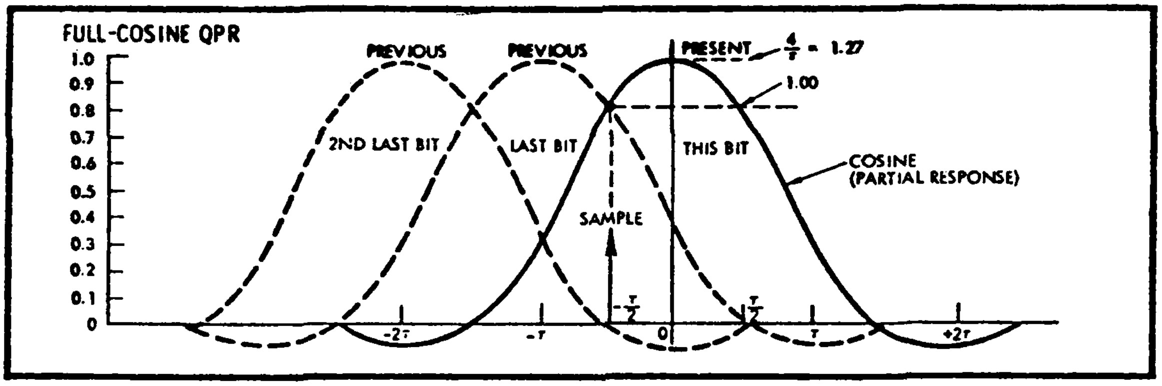
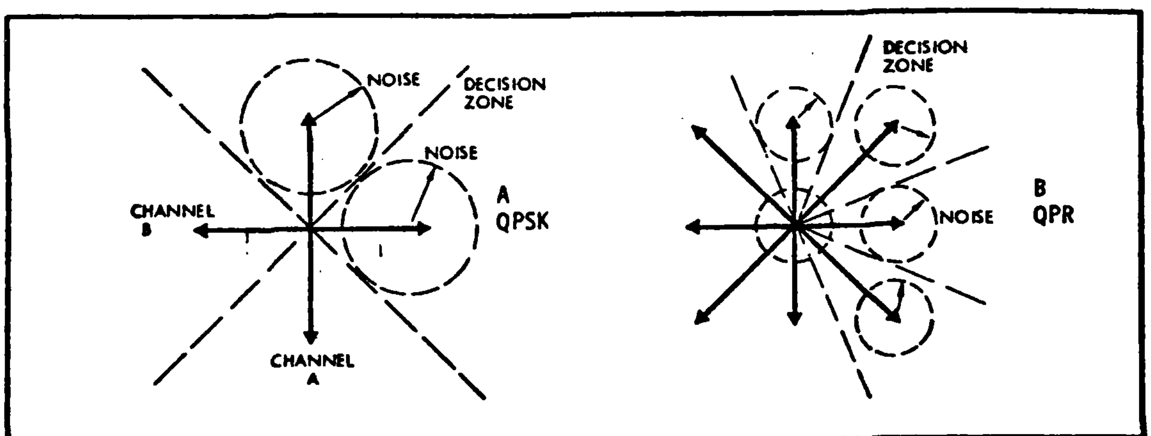


Figure 1. 3— Level Partial Response Baseband Signal





(a) QPR **Baseband Filter Intersymbol Response**



(b) RF SIGNAL CONSTELLATIONS (QPSK AND QPR)

Figure 2. QPR Modulation Characteristics

2. AN/FRC-( )( ) HYBRID COMPUTER SIMULATION

The AN/FRC-( )( ) LOS Radio design is being used to modify the existing QPR radio hybrid computer simulation under a DCS RDT&E effort by Martin-Marietta, Inc. Figure 3 is a block diagram of the simulation, a brief description of which follows below. A pseudo-random data stream (PRDS) representing digital traffic is generated in Module I of the simulation. In Module 2, the PRDS is scrambled using a self- synchronizing scrambler, split into cophasal and quadrature branches and differentially encoded. Up to this point the information is still in binary form. In Module 3, the cophasal and quadrature bit streams are presented to separate impulse modulators (actually pulse generators which generate very short pulses at the quadrature data rates). The outputs of the impulse modulators are presented to separate low pass filters which transform the binary cophasal and quadrature branches into three level baseband signals. In Figure 4, photographs of the impulse response of the low pass filter are presented. (The hybrid computer simulation is an actual QPR system, scaled down in frequency.) Finally, in Module 3, the cophasal and quadrature bit streams are phase modulated onto a scaled IF (representing the actual 70 MHz IF of the AN/FRC-( )( ) radio). Figure 5 is a photograph of the QPR spectrum at the output of the modulator. Module 4 represents the RF stages of the AN/FRC-( )( ) transmitter and includes a bandpass nonlinearity to represent the TWT RF amplifier amplitude together with post amplification filtering. The amplitude and phase nonlinearities simulated are shown in Figure 6.

Module 5 simulates the RF stages of the AN/FRC-( )( ) receivers. Dual receivers are simulated to represent the dual diversity configuration of the radio and contain the IF filters (to provide frequency selectivity) as well as the Automatic Gain Control (AGC) function. In Module 6, the simulated IF QPR signal is demodulated by the modified Costas loop quadrature demodulator chosen by the AN/FRC-( )( ) contractor. Module 6 also contains the carrier recovery and tracking circuitry and like Module 5, has redundant circuits to simulate a dual diversity radio configuration. The output of Module 6 is the analog version of the three-level partial response baseband which has an "eye pattern" representation, as seen in Figure 7. In Module 7, the diversity three-level basebands are regenerated by slicers, bit timing is recovered, and the now-digital three-level signals are decoded into several binary forms. Also, in Module 7 the diversity bit streams are descrambled for processing in the diversity switch.

In Module 8, in-service performance of the dual diversity bit streams is monitored. This module implements psuedo-error rate and AGC monitors for each of the diversity bit streams, and, based on a preprogrammed algorithm, develops a control voltage which is used to select the better diversity path in the AN/FRC-( )( ) diversity

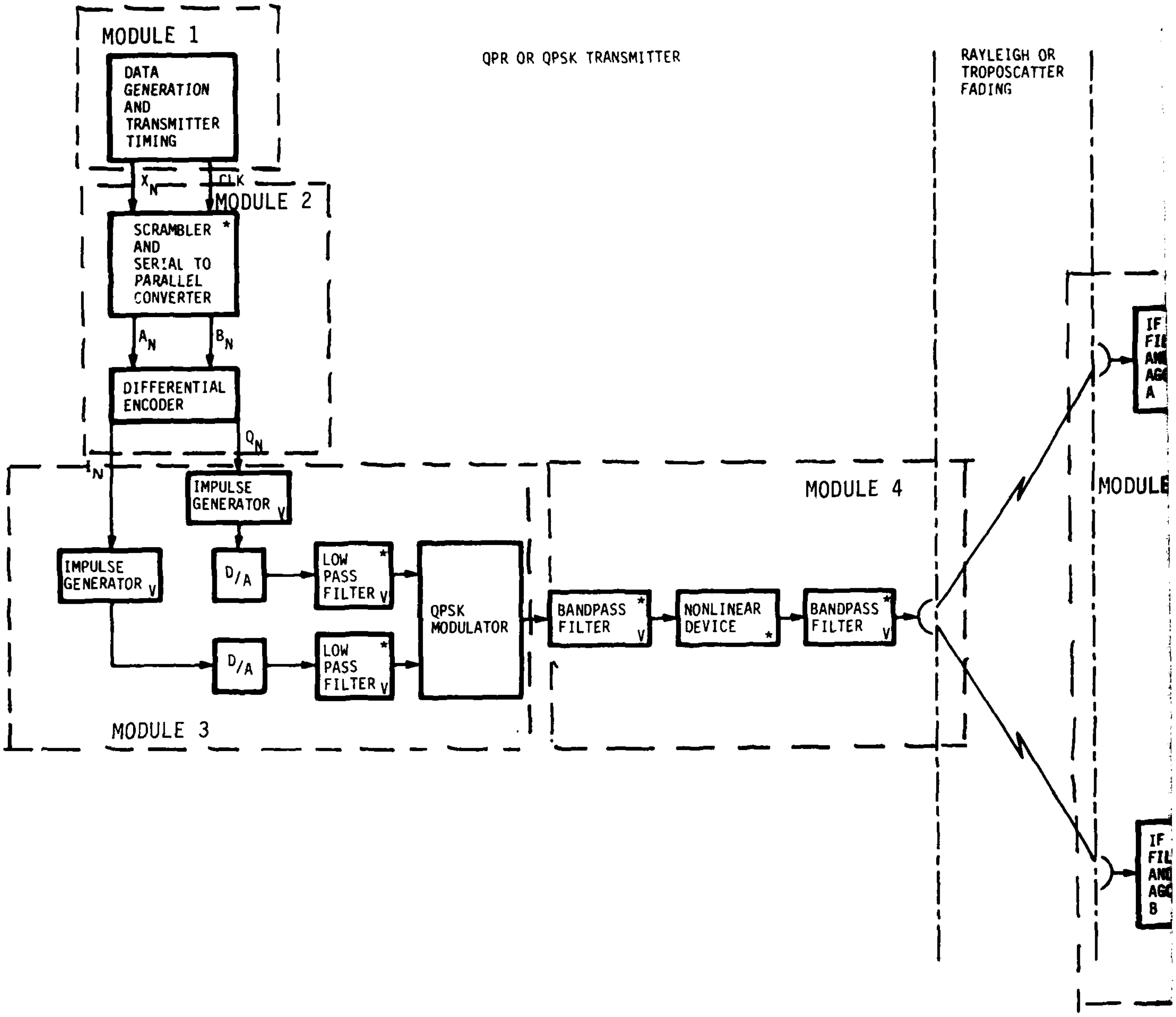


Figure 3. QPR and QPS

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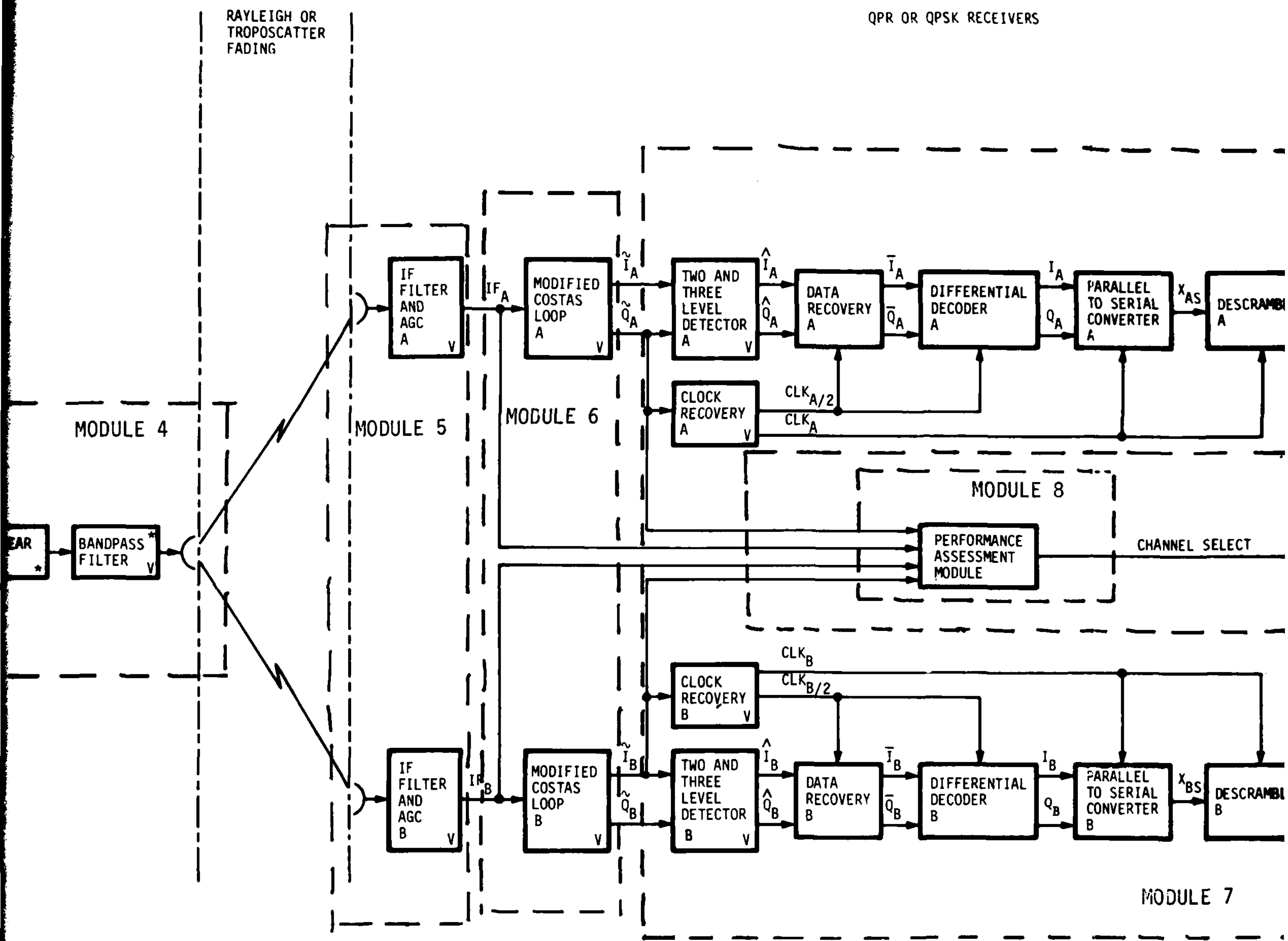
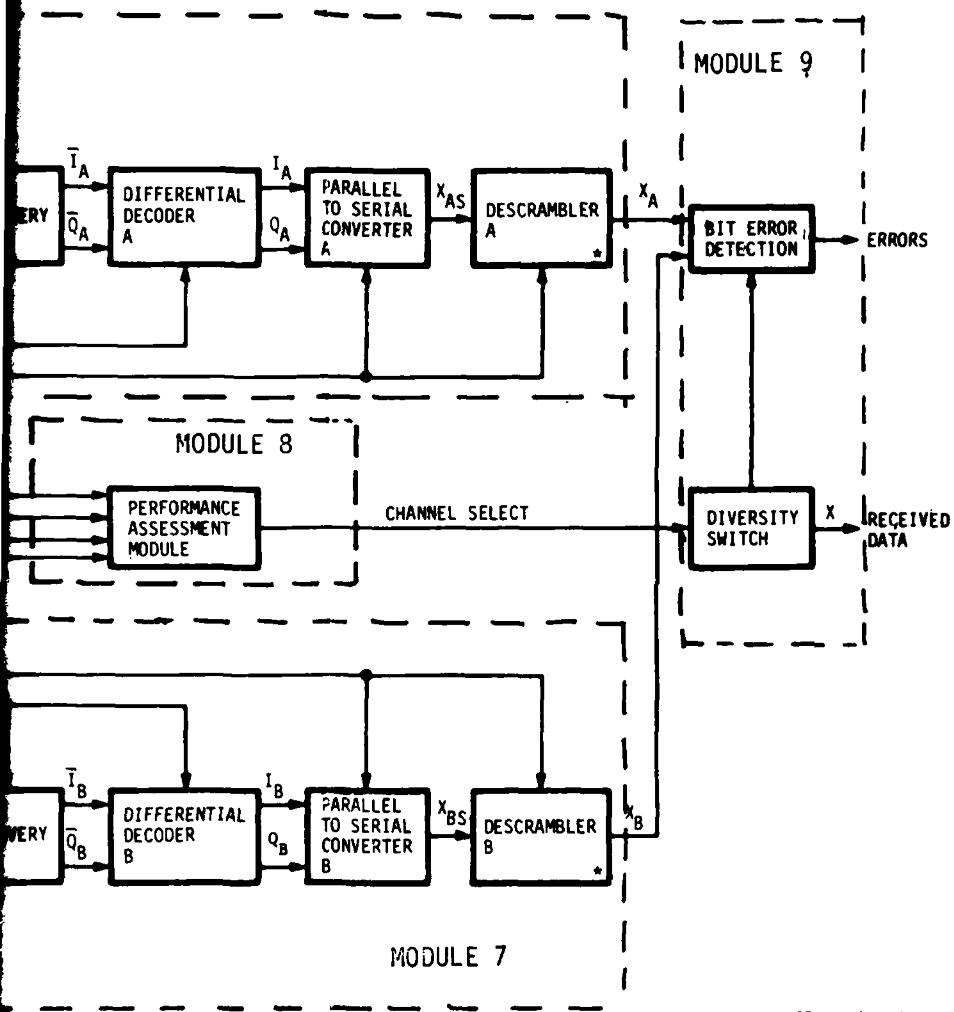


Figure 3. QPR and QPSK Dual Diversity Simulation

3

QPR OR QPSK RECEIVERS



* - OPTIONAL MODULE

V - VARIABLE MODULE

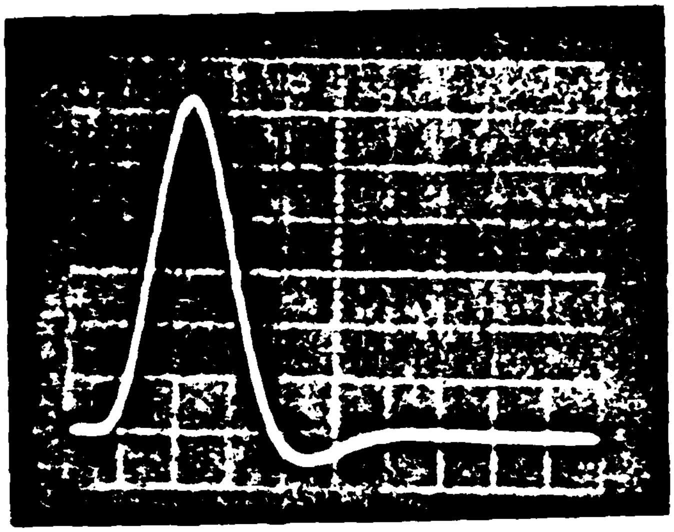


FIGURE 4. Simulated Partial Response Filter Impulse Response (Measured)

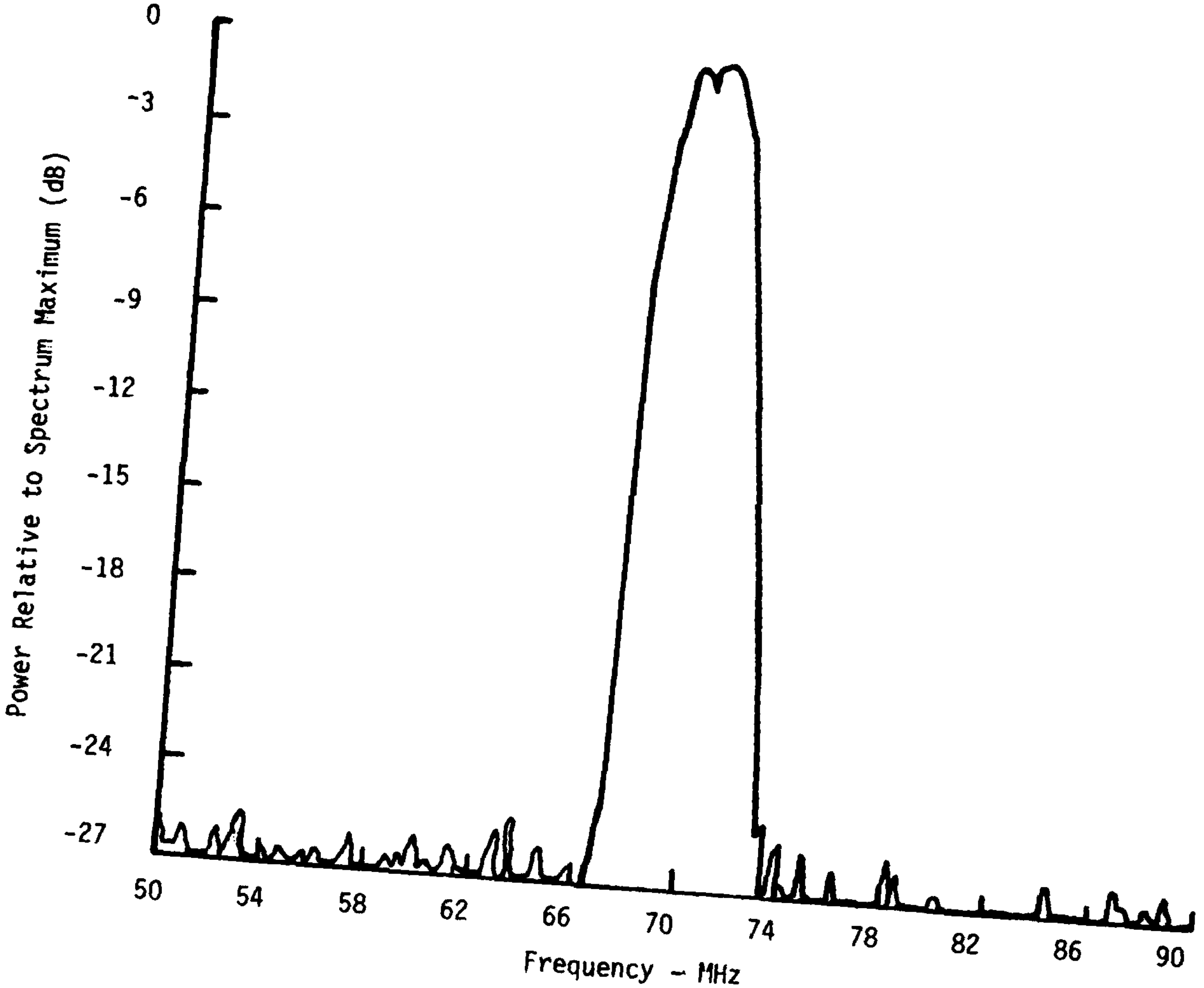
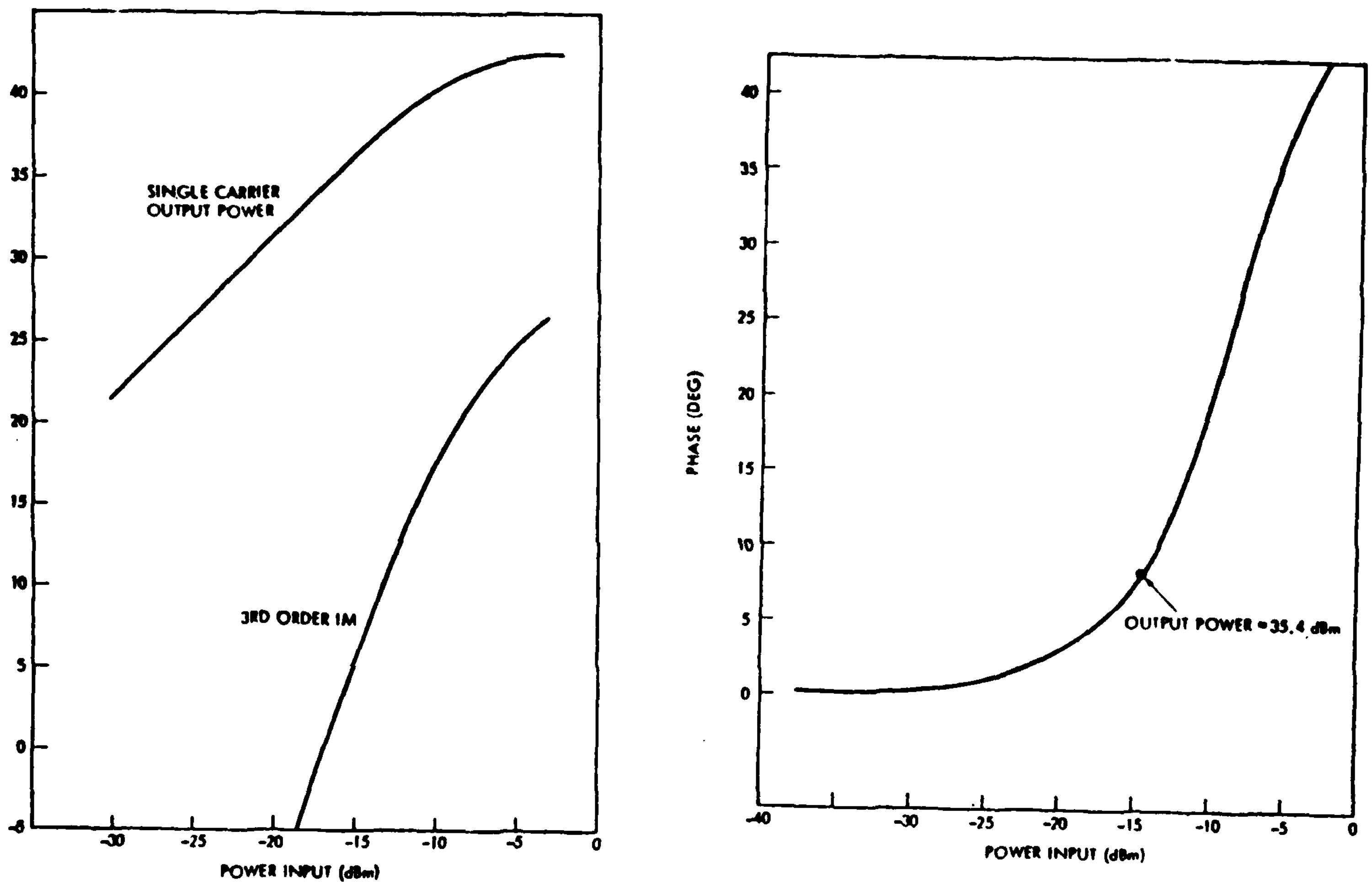


Figure 5. QPR IF Spectrum (2 Bits/Cycle)

combiner. The algorithm for the AN/FRC-( )( ) was developed at DCEC and is described by J. Osterholz (5). In Module 9, the AN/FRC-( )( ) dual diversity combiner is simulated. It is a selection combiner and utilizes digital buffers and a clock averaging circuit to insure that transient free diversity switching is accomplished.

As the simulation is implemented on a hybrid computer the operating frequency and bit rate must be scaled down. In this case, the simulation bit rate is 1000 b/s representing 26 Mb/s, and the carrier frequency is nominally 50 kHz. A baseline Bit Error Rate (BER) curve in additive Gaussian noise is shown in Figure 8, along with a theoretically derived QPR curve. The simulation accurately represents QPR performance.



A) AMPLITUDE

B) PHASE

Figure 6. Amplitude and Phase Characteristics of Traveling Wave Tube for AN/FRC-()() Radio

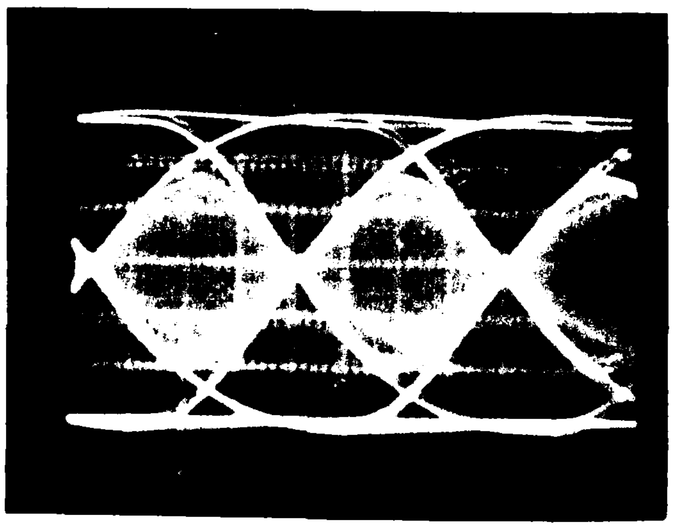


Figure 7. QPR Eye Pattern (Transmit)

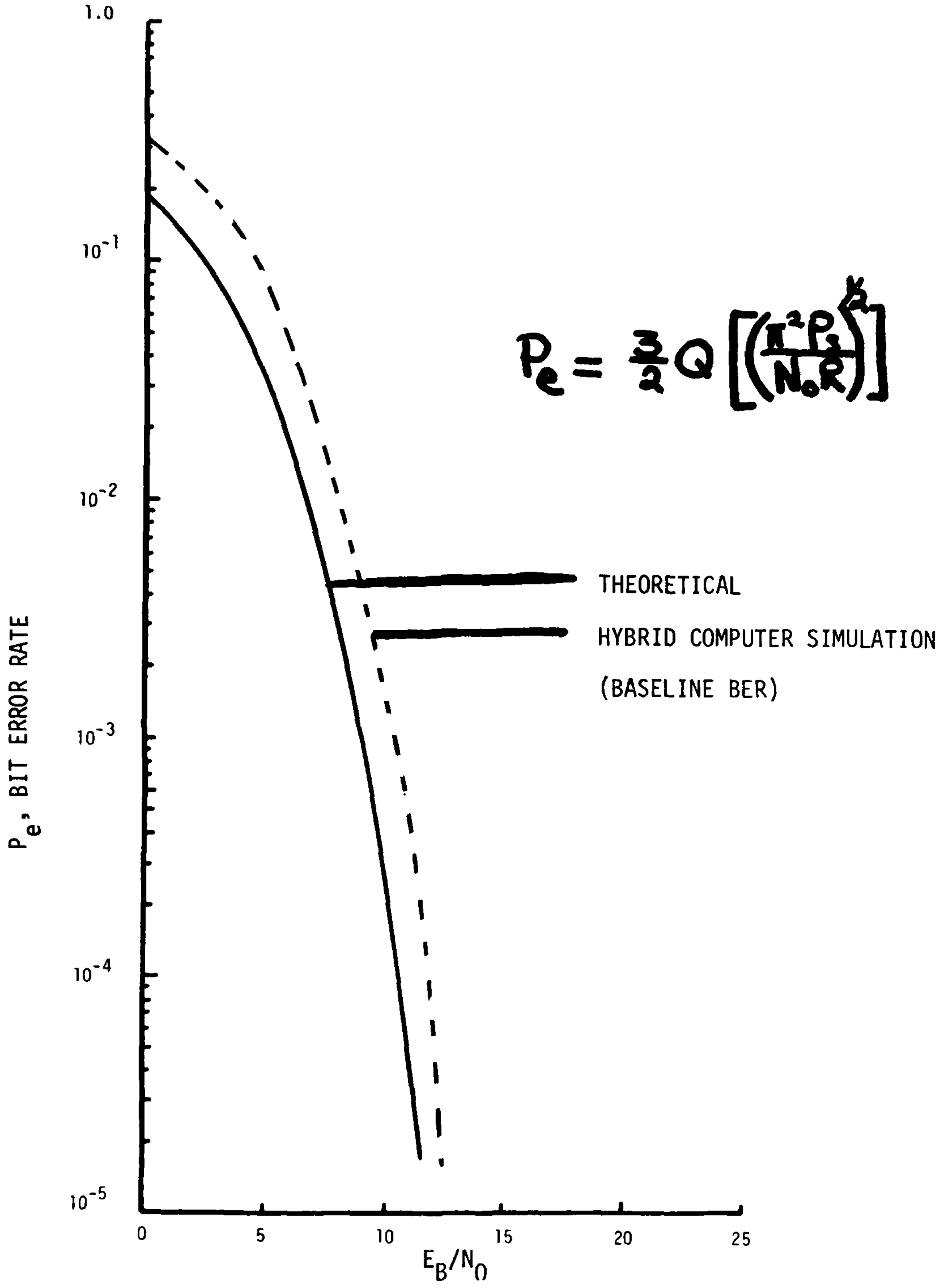


Figure 8. QPR Simulation Performance

IV. FREQUENCY SELECTIVE FADING ON DIGITAL LOS LINKS

1. INTRODUCTION

The phenomenon of frequency selective fading has important consequences for both analog and digital communications. The presence of frequency selective fading allows the use of frequency diversity in both digital and analog systems to reduce the overall dynamic range of propagation channel fading. For analog systems, frequency selective fading within the modulation bandwidth will cause intermodulation distortion (IMD) and result in an increase in the overall noise power of the system. For digital systems, frequency selective fading within the modulation bandwidth will cause intersymbol interference (ISI) and increase the overall system Bit Error Rate (BER). Both IMD and ISI cannot be mitigated by an increase of system gain, since the source of the degradation is the signal itself. A digital transmission system operating in a region where ISI limits performance will exhibit a constant bit error rate which is independent of both thermal noise and transmitted power.

A number of studies have addressed the phenomena of frequency selective fading (and its Fourier dual representation, time dispersion) for the special case of the tropospheric scatter fading channel (8). Recently, however, it has become apparent that frequency selective fading may also be an important consideration for the Line of Sight (LOS) microwave channel which is typically modeled as a Rician channel with a large "nonfading" or direct component. This section addresses LOS microwave propagation by examining the basis for frequency selective fading (or its time based equivalent, time dispersion) in the Rician fading channel. Although the LOS microwave channel is emphasized, the derivation presented herein is kept sufficiently general to permit adaption to other propagation channels of interest. The model presented herein is a refinement of the model originally derived during the system engineering of another digital LOS System (9).

2. LOS CHANNEL MODEL

The assumptions implicit in this model of the time dispersive fading LOS channel, which is shown conceptually in Figure 9, are:

a. The LOS channel comprises a "direct" component which propagates over the LOS path and a "delayed", time dispersive component arising from refraction or reflection from elevated tropospheric layers or other atmospheric irregularities.

b. The direct component, while appearing to be nonfading over a period of a few minutes, actually exhibits a slow variation in intensity with a relatively large (30-40 dB) dynamic range. The mean intensity of the time dispersive component is normally much lower and

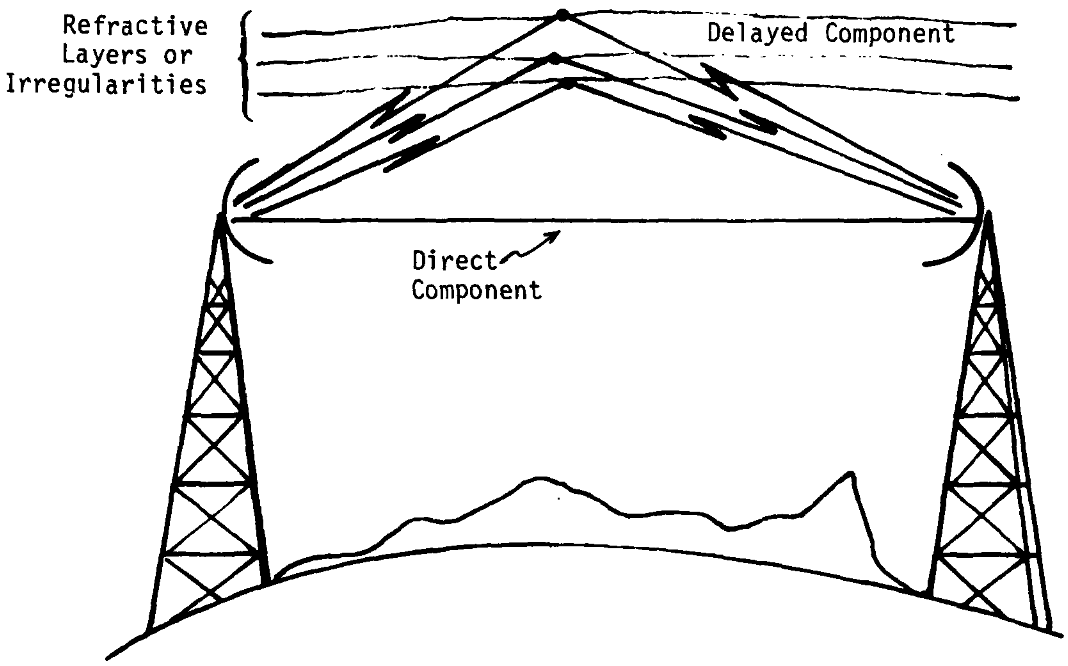


Figure 9. Microwave LOS Propagation Model

is assumed constant. The slow deep fading of the direct component may result from refractive terrain blockage or from degeneration of the direct component into two (or more) components with differences in path propagation time (e.g., a few half wavelengths) which are large enough to cause destructive RF interference but small enough to neglect from a time dispersive viewpoint.

c. The differential time delay between the specular and time dispersive component epochs is dependent on the heights of the link antennas, the height of the elevated refractive region, prevalent refractive index lapse rates, and link antenna bandwidths. This delay can vary from zero upward, depending on the meteorology prevalent on the link.

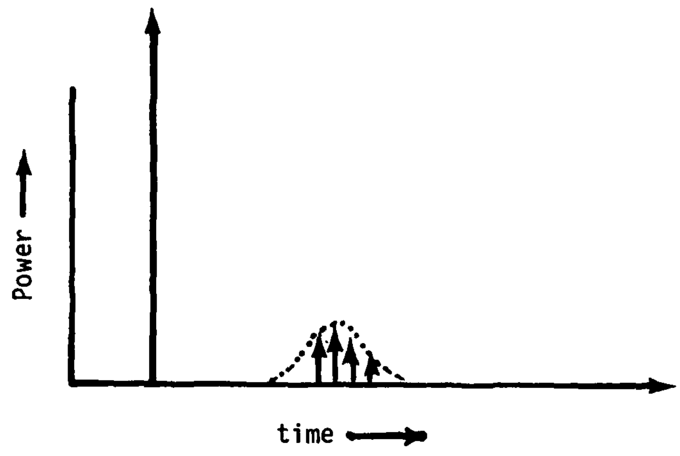
d. The temporal width of the time dispersive component is related to the number of layers of the threshold refractive region and their dimensions, the terminal site locations, and the antenna beamwidths. This relationship is similar to that proposed by Bello (9) for dispersive troposcatter propagation caused by refraction from elevated layers or turbulent scattering from refractive irregularities.

The normal or "non-faded" appearance of this channel in the time domain is shown in Figure 10(a). Because the power of the specular component is normally much greater than the power in the dispersive component, the LOS channel during nonfading and shallow fading periods appears highly non-time dispersive (i.e., non-frequency-selective). However during deep fades, as seen in Figure 10(b), the time dispersive nature of the channel becomes more apparent. During selective fading events, it is postulated that the direct path will have faded 20-30 dB to the point where the ratio of direct path component power to dispersive component power is then 10 dB or less.

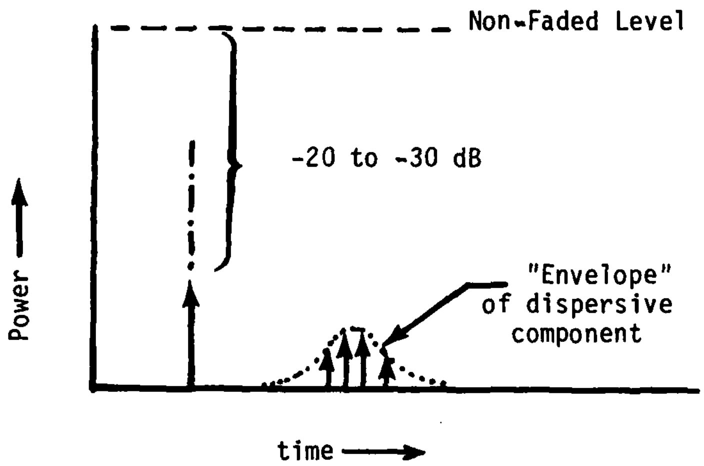
Of specific interest is the effect that a direct path fade can have on the overall time dispersion of the channel. For analytical purposes, the envelope (in time) of the dispersive component (which is assumed to be an ensemble average of delayed echoes of the transmitted signal created within the refractive region) will be described as having a shape consistent with the shape of the delay power spread derived by Bello [9].

I.e.,

$$\Gamma(t) = \frac{2t}{\sigma_D^2} \exp\left[\frac{-\sqrt{2}\,t}{\sigma_D}\right] \qquad (1)$$



(a) UNFADED STATE



(b) FADED STATE

Figure 10. Microwave LOS Time Response

Where the quantity $2\sigma_D$ is defined as the significant extent of the time dispersive component, the mean delay of the dispersive component, τ_d, is found by calculating

$$\tau_d = \int_0^\infty t\Gamma(t)dt. \tag{2}$$

For the shape assumed in equation (1), τ_d is then

$$\tau_d = \sqrt{2}\ \sigma_D.$$

Other functions could be used to model the time dispersive component. However, the sensitivity of the final result to the choice of function was not found to be significant.

As shown in Figure 10(b), the overall time response of the composite channel can be described as $P_D\Gamma\ (t) + P_L\delta\ (t-\tau)$ where P_D and P_L are the normalized dispersive and direct (LOS) component powers respectively.

The mean delay of the composite LOS channel relative to the epoch of the refracted component can be written as

$$\tau_C = P_D\ \tau_d - P_L\tau \tag{3}$$

where τ is the mean differential delay between the direct component and the epoch of the refracted, time dispersive component.

Similarly, the variance of the composite channel delay can be expressed as

$$\sigma_C^2 = P_D\ (\sigma_D^2 + \tau_d^2) + P_L\tau^2 - \tau_C^2 \tag{4}$$

where $P_D + P_L = 1$.

Letting $r = P_L/P_D$,

$$P_L = r/1+r \text{ and } P_D = 1/(1+r).$$

Combining equations 3 and 4, we can express the 2σ dispersion of the composite channel as

$$\delta_r = 2\left[\frac{1}{(1+r)^2}\left[(1+3r)\sigma_D^2 + 2\sqrt{2}\,\sigma_D\tau r + \tau^2 r\right]\right]^{\frac{1}{2}}. \qquad (5)$$

Thus, δ_r can now be calculated, given knowledge of σ_D, τ, and the range of r expected on a particular propagation path. In general, it is seen that the composite channel delay "spread", δ_r, increases as r decreases, with a maximum delay spread occuring as r is approximately unity. Interestingly, it is seen that further reduction in r (i.e., very deep fading) will actually result in a decrease in δ_r, although at a much smaller rate. As an example, in Figure 11, δ_r is calculated for various hypothetical values of r and $2\sigma_D/\tau$.

The remainder of this section will describe the considerations involved in estimating σ_D, τ, and r for the microwave LOS channel, and the comparison of predicted time dispersion with measured values reported by Bell Telephone Laboratories. As an example, consider a hypothetical LOS link of length d, with equal height transmit and receive antennas. An elevated refractive layer structure is presumed to be at a mean height h_ℓ and to extend horizontally over most of the path. The differential delay, τ, between the direct component and the epoch (i.e., first arrival) of the refracted component can be estimated as

$$\tau = \frac{\Delta\ell}{C} \cong \frac{\left|d - \left[\sqrt{(h_\ell - h_\alpha)^2 + d_\ell^2} + \sqrt{(h_\ell - h_\alpha)^2 + (d - d_\ell)^2}\right]\right|}{C} \qquad (6)$$

where h_α = Height of the antenna center line.
d_ℓ = Mean distance from the transmitter at which the transmitted signal intersects the refractive boundary.
c = Speed of light.
$\Delta\ell$ = Differential path length between direct and refracted components.

d_ℓ can be approximated from knowledge of the antenna beamwidth θ, and the layer height, h.
I.e.,

$$d_\ell \cong \frac{h_\ell}{\tan\theta} \qquad (7)$$

Note that this expression assumes that dispersion results from refraction of a portion of the main beam and neglects contributions from the antenna side lobes which propagate over a much greater solid angle than the main beam. However, for the typical long haul case of larger, highly directive antennas with shroud suppressed side lobes, this assumption is considered acceptable to first order.

Having developed an approximate expression for τ, we provide an expression for time dispersion of the refracted component, σ_D.

Since it has been assumed that refraction from a layer in the lower portion of the troposphere is responsible for the existence of the residual component, an adaptation of the work of P. Bello appears appropriate for use in estimating σ_D.

Bello (8) defines a quantity called $Q(\alpha)$, or the Delay Power Spectrum (DPS). The DPS is defined as the average value of the impulse response of the time varying refractive component. From the DPS, we can define the effective multipath spread, σ_D, which was referred to earlier, as

$$\sigma_D = \frac{\alpha^2 Q(\alpha)d\alpha - \left[\int \alpha Q(\alpha)d\alpha\right]^2}{Q(\alpha)d\alpha} \tag{8}$$

The structure of $Q(\alpha)$, and hence the magnitude of σ_D, is related to a number of factors such as the "effective earth radius", the refractive gradient of the refractive layer structure, the angle at which the link antennas are elevated relative to the horizontal, the beamwidths of the link antennas, and assumptions as to the relative turbulence of the refractive process. For specific details of this model, the reader is recommended to reference (9). A computer program suitable for use in computing $Q(\alpha)$ is provided in Appendex A.

As an example, consider the hypothetical link described in Table I. Applying the estimation relationships derived herein, we find τ to be on the order of 1.7 nsec. Similarly, the application of Bello's formula for σ_D provides a value of 6.2 nsec. Since the direct and refractive components are additive in proportion to their relative strengths, the relationship defined by equation 5 can be applied. The results are shown in Figure 11. Note that the maximum multipath dispersion occurs when the direct and refracted paths have nearly equal power. The model predicts a maximum multipath dispersion for the link of 14.8 nsec (i.e., δ_r) which is in reasonable agreement with the value of 12.4 nsec observed by Kaylor on a nominal 30 mi. LOS path (10).

TABLE I. HYPOTHETICAL LOS LINK PARAMETERS

Frequency	8GHz
Path Length	30 mi.
Antenna Height	100'
Mean Layer Height	1000'
Terrain/Climate	Average/temperate

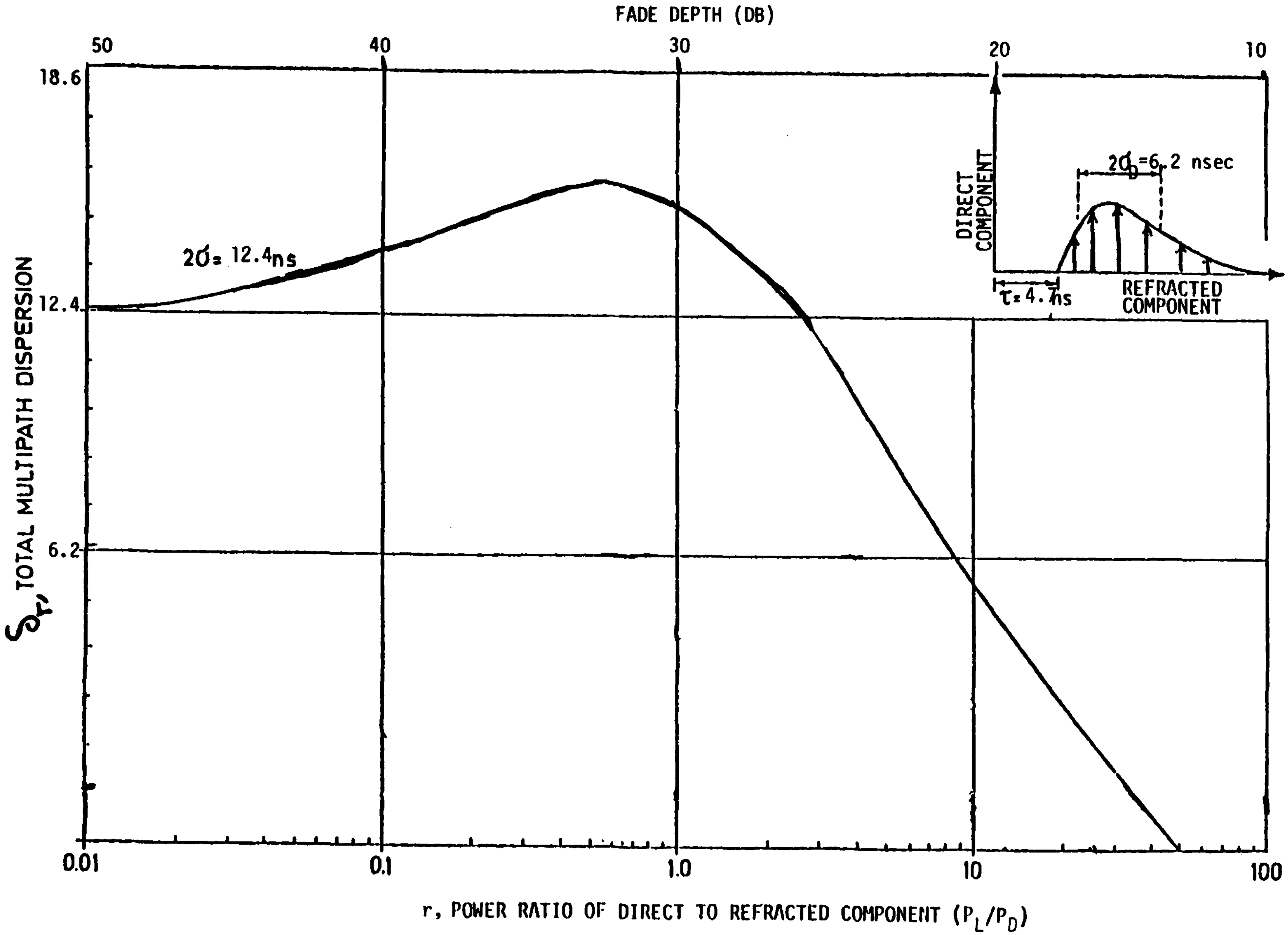


Figure 11. Fading and Multipath Delay - 30 Mile Link

Of course this estimate of maximum dispersion does not address the frequency at which various values of multipath dispersion can occur. Reexamining Figure 11, we see that the overall multipath delay is strongly affected by the strength of the direct component. Thus, fading in the direct component (because of multipath between closely spaced rays in the direct component or perhaps obstacle blockage of the direct path) would result in increasing delay. The question of frequency is then related to the probability of direct path fading. A reasonable assumption, which has been supported by numerous narrowband measurements, is that the probability of a direct path fade, P(F), is as described by Barnett (11).

I.e., $P(F) = bm \times 10^{-F/10}$

$$\text{where } m = a\times10^{-5} \times F/4\times D^3 \tag{9}$$

a = terrain factor (= 1 for average terrain)
f = frequency in GHz
D = path length in miles
b - represents the percentage of the year occupied by the fading season (= .25 for temperate climate)
F = fade depth in dB.

Note that by this formulation, the occurrence of moderate delays is expected to be strongly correlated with fade depth (i.e., direct path loss) during shallow and moderately deep fading, and weakly correlated in the very deeply faded region. The expected weak correlation during very deep fading results from the dominant influence of the refracted component(s) which tend to fluctuate independently among themselves and also with respect to the highly attenuated direct path. A similar correlation between path loss and multipath dispersion for tropospherically refracted signals has been established previously. Note also from this model that multipath dispersion can potentially become excessive and cause higher bit error rates than would be expected at equivalent fade depths without the added dispersion.

For the non-diversity LOS path described in Table I, with nominal 8 GHz, 30 mile average terrain and climate, the probability of a fade is approximately $1.3 \times 10^{-1} \times 10^{-F/10}$ where F is the fade depth in dB. Assuming that equation 9 adequately expresses the relationship between fade depth and its frequency of occurrence (actually the power ratio of the direct to refracted delayed path), the probability of observing various multipath delays can be estimated. As an example, a 20 dB fade should result in a P_D/P_L of about 10 dB (a factor of 10). For the 30 mile path, this should cause a total multipath delay of approximately 7.5 nsec. If the main path fades 30 dB, the overall delay increases sharply to nearly 12 nsec. As seen in Figure 12, for the typical 30 mile link, fades of 30 dB or greater (i.e., delays of 12 nsec or greater) are expected (using equation 9) with a probability of about .0001 on a yearly basis and four times greater, .0004, during the worst month (i.e., about 1000 seconds).

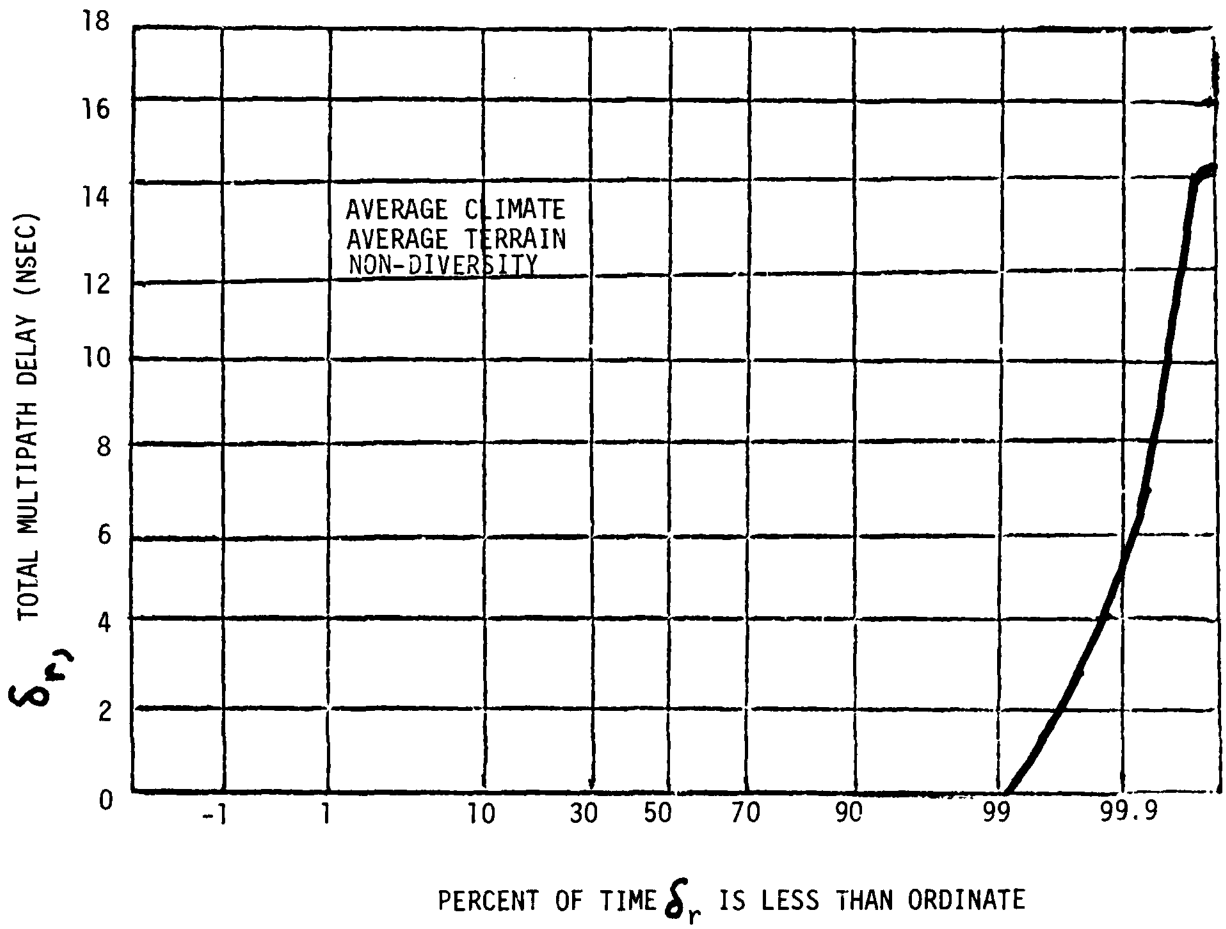


Figure 12. Multipath Delay Distribution (30 Mile Link)

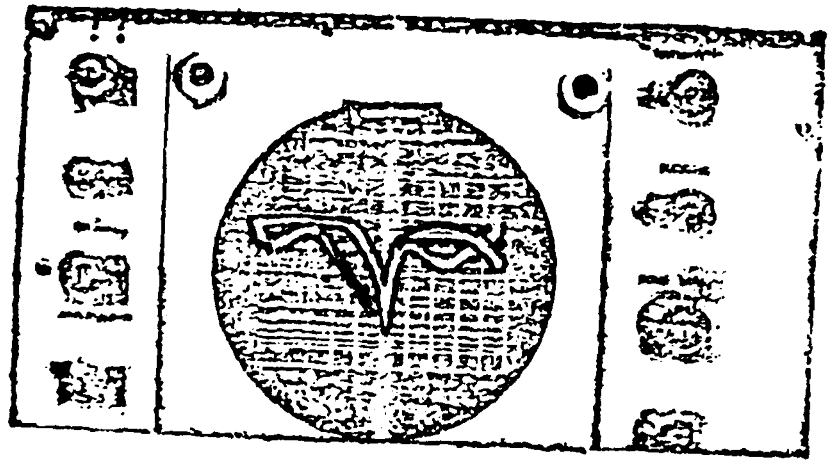
The delays and their associated probabilities are predicted to increase sharply with increasing distance. As an example, consider a 45 mi. (75 km) link in the 7-8 GHz band. The maximum delay for that link is estimated to be on the order of 25 nsec. A 20 dB fade would result in a delay of almost 14 nsec. Fading to a depth of 20 dB or more can be expected to occur with a probability of .0046 per year or about .0184 during the worst month. A fade of 30 dB would be expected to result in nearly the maximum delay (about 25 nsec) and should occur with a probability of .00046 per year, or .00184 during the worst fading month. The predicted delay dependence on path length can critically affect the design of DCS links and must be subjected to experimental verification before firm conclusions can be drawn.

3. POTENTIAL COMMUNICATIONS EFFECTS

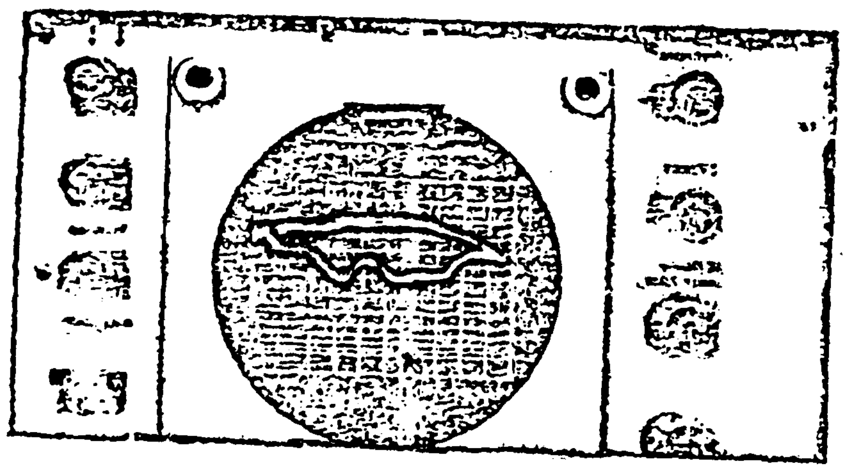
Frequency selective fading will cause variations in the amplitude and delay characteristics of the LOS channel. Such variations can have the same effect on both wideband analog and digital systems - a reduction in performance. For many digital modulation techniques, such as QPSK and QPR, the effect can be serious, particularly if a high degree of coherency is required in the receiver between the carrier reference and the received signal. Under these conditions, noncoherent detection methods such as radiometric (energy) detection or use of a limiter/discriminator (for angle modulated systems) offer increased protection. Thus, while coherent modulation techniques such as 8 PSK and QPR may be more efficient under additive noise conditions than noncoherent techniques such as Differential PSK (DPSK) or Four Level FM with frequency discriminator detection, operation in a frequency selective fading channel can potentially reduce efficiency.

The amplitude and group delay response of a deeply faded microwave LOS channel can be extremely severe, as can be seen in Figure 13. The amplitude response of the deeply faded LOS channel can exhibit both "notch" type fading (where a narrow portion of the transmitted spectrum fades) or "slope" type fading where there is a monotonic decrease in amplitude response across large portions of the spectrum. As expected, the group delay response for notch type fading will be by far the most severe. Unfortunately, due to the relatively few reflected or refracted components present in significant intensity during a typical LOS fade, most deep fading events are expected to be of the notch type with the attendant severe group delay.

To mitigate the effects of multipath fading, space, or occasionally frequency, diversity transmission is normally employed on long haul LOS radio systems. Key to the performance of the diversity scheme is the effectiveness of the diversity combiner implemented in the radios to combine signals received over diversity



a. (with Selective Fading)



b (Normal - UNFADED)

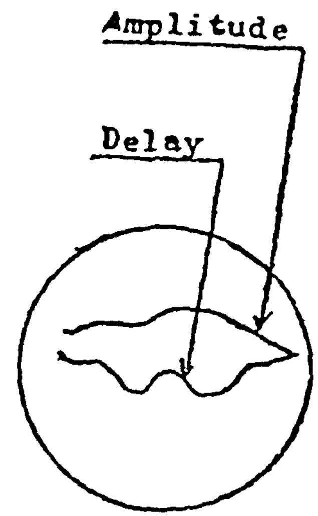


Figure 13. LOS Multipath Fading Amplitude/
Delay Characteristics

channels. The diversity combiner used in the AN/FRC-( )( ) is a selection combiner. The selection combiner is actually a switch which intelligently selects the "best" diversity channel out of a received set of inputs and provides the selected channel to downstream multiplexing equipment. The selection diversity combiner can also be used to provide a protection switching capability in the event of a receiver failure. For discussion purposes, the AN/FRC-( )( ) selection combiner can be thought of as comprising the following key elements.

- Diversity Channel Performance Monitor
- Diversity Selection Control Processor
- Diversity Switch.

Fading has a significant and unique impact on each of the aforementioned elements of the diversity combiner. However, a frequency selective characteristic of the fading has an even more basic, but much less understood, impact. In the following paragraphs, frequency selective fading is addressed as it relates to the design of each of the key diversity combiner elements listed above.

For FDM/FM systems with passbands sufficiently narrow to be unaffected by frequency selective fading, the use of receiver Automatic Gain Control (AGC) to monitor the "quality" of each of the input channels is often sufficient. High rate digital systems, however, can be affected by frequency selective fading and therefore reliance on receiver AGC as a performance monitor is not practical. This follows because receiver AGC circuits generally respond to the total passband power and not to degradations in the quality of the passband itself. Thus, receiver AGC will not accurately respond to baseband degradations such as interference and frequency selective fading. The use of pseudo-error or offset threshold monitoring (OTM) techniques to assess the performance of digital channels is much more effective and has been explored extensively, first by Gooding (12), and subsequently by Leon, et al (13), Smith (14), and Osterholz (5). In Figure 14, which is a hybrid simulation of an offset threshold monitor response to a frequency selective fading channel, the OTM accurately detects bit error events resulting from selective fading while AGC fails to indicate the events. However, while the OTM technique is, in principle, sensitive to intersymbol interference (ISI) resulting from frequency selective fading, it must be implemented in a manner which will provide the following characteristics:

- Sufficient dynamic range to cover all practical parameter variations.

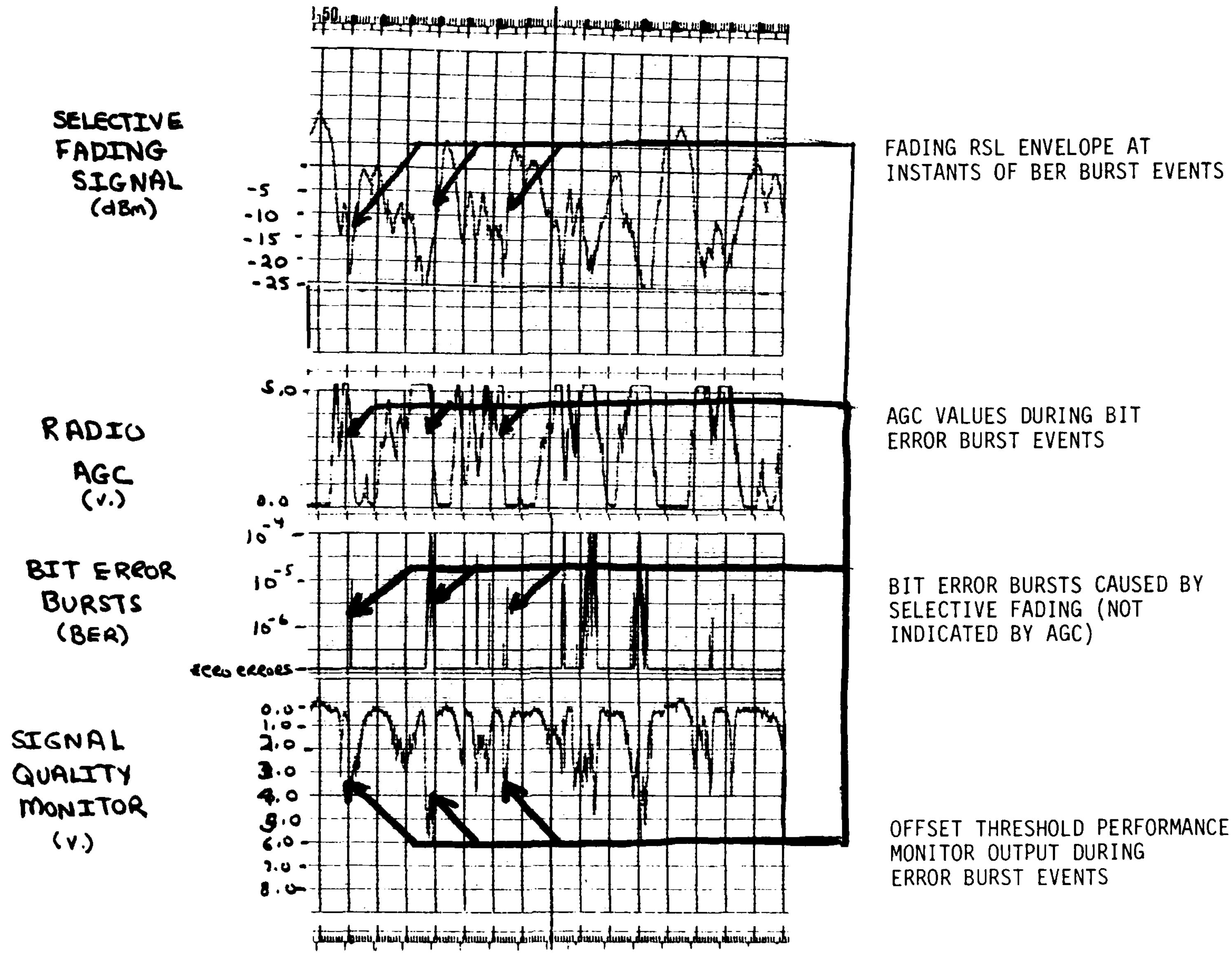


Figure 14. Offset Threshold Monitor Fading Response

- Proportionality to baseband SNR.
- Single valuedness under various degradations (additive noise, ISI, cochannel and adjacent channel).
- Speed and accuracy to permit early and reliable detection of a fade event.

Other techniques such as baseband code violations and parity checks can be used to assess diversity channels. Whatever technique is chosen must nonetheless meet the criteria listed above if the diversity selection operation is to be effective.

If the performance monitor technique chosen had infinite dynamic range and infinitesimal resolution, the choice of a diversity control algorithm would be trivial. Unfortunately, in order to effectively function over the range of inputs where diversity operation is required, the necessary dynamic range and resolution of the combiner will most likely exceed the dynamic range and resolution capability of any single performance monitor technique. The choice of diversity control algorithm becomes more complex under that situation, and also because it must utilize more than one monitor technique. Critical to the effectiveness of the diversity combiner is the choice of a "hand-over strategy" between monitor techniques. The hand-over could, as an example, be based on an assessment of the limited dynamic range of each of the monitors as proposed by Osterholz (5), or it may be based on a "hard wired" transition point. Whatever the choice of control algorithm, it must provide the maximum overall dynamic range and accuracy over the widest possible range of input degradations.

The diversity "switch" is that functional element that receives a signal from the diversity control processor (derived on the basis of a control algorithm) and switches to the chosen channel on a hitless basis (that is, no errors or loss of Bit Count Integrity (BCI) are generated as a result of the switching action).

To maintain BCI, the combiner must insure bit stream alignment during the switching operation. Under frequency selective fading, the timing epochs of the unfaded and faded diversity channels may differ on a time varying basis. Thus, some degree of "elasticity" must be built into the switch to accommodate the differential time delay. Based on the channel model developed earlier in this section, the early detection of a fade would minimize the requirement for elasticity (logically assuming the deeper fades cause larger shifts in bit timing epoch). However, the effects of differential bit delay can never be completely eliminated and therefore some sort of clock adaption is indicated, even if it is only clock averaging.

V. HYBRID COMPUTER SIMULATION OF SELECTIVE FADING

1. INTRODUCTION

In this section, the simulation of frequency selective fading using a digitally controlled analog computer (i.e., a "hybrid computer") will be briefly discussed. As in any hybrid computer simulation, the desired simulation characteristics are achieved through the use of active components (e.g., mixers, analog function generators, active filters) which operate on the input modulated signal to cause portions of it to fade, be delayed with respect to the other portion, and so on. The digital portion of the simulation provides the simulation control signals used to effect rapid changes in propagation fade rate, signal to noise ratio, and if a digital delay scheme is used, clock signals which time propagation delays between direct and refracted components. The basic simulation circuitry for the LOS model, described herein, is shown in Figures 15, 16, and 17 which illustrate the overall channel simulation, the component delay module, and the component fading module respectively.

2. HYBRID SIMULATION CONSIDERATIONS

To implement the hybrid computer simulation described by Figures 16 through 17, identification of certain critical simulation parameters and ranges is necessary. Of particular importance is the selection of direct and refracted component fade rates, direct to refracted component power ratio, and fading correlation between the dual diversity channels. This section identifies initial values and ranges for each of these parameters and briefly summarize the rationale for the choices.

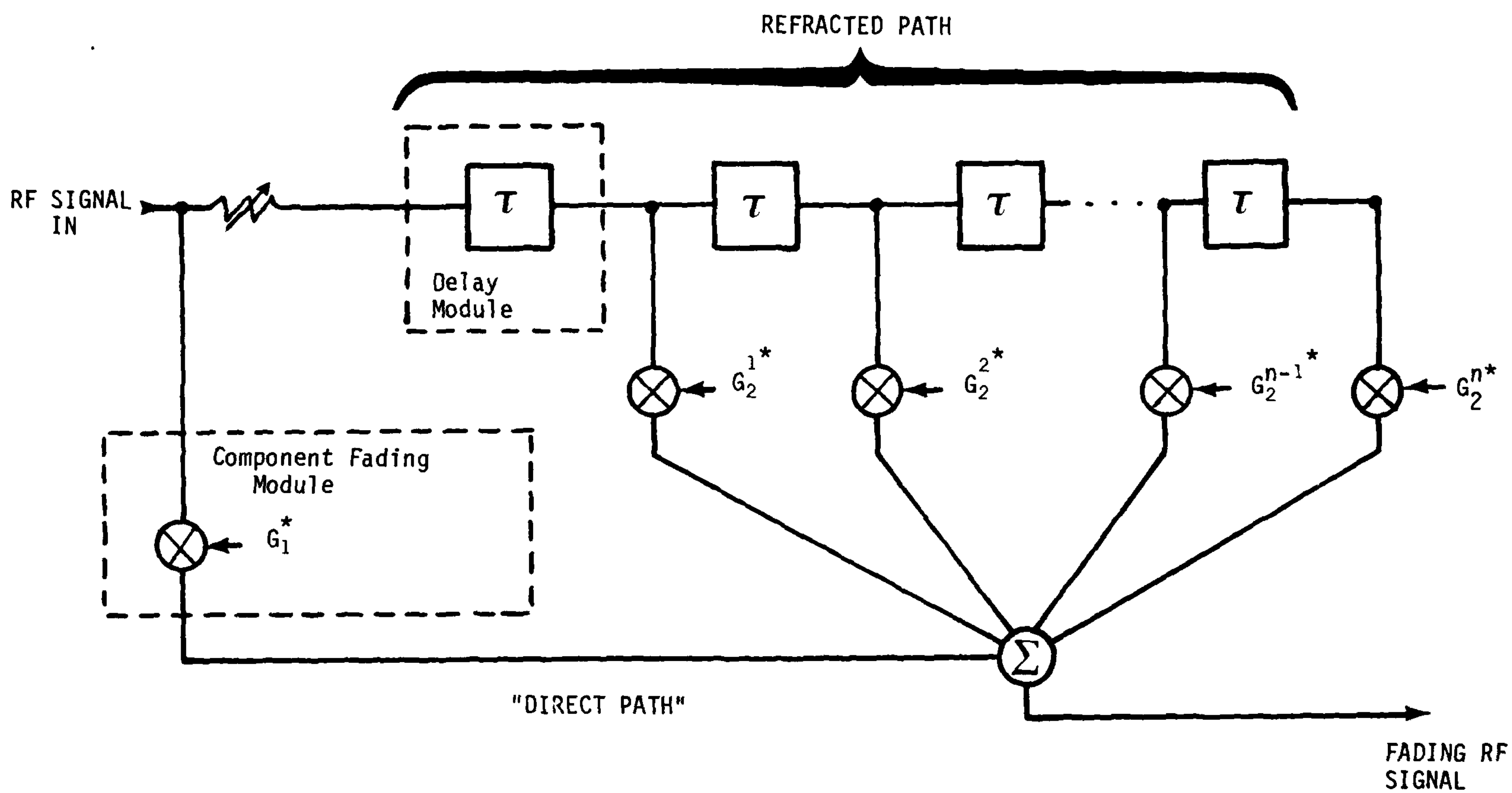
The fade rates of the direct and refracted paths are assumed to be unequal. This phenomenon is revealed by numerous studies which indicate that the RSL variation during shallow fades (excluding scintillations) is generally slower than the RSL variation experienced near the bottom of deep fades (e.g., where the refracted and direct components have near equal powers). The quantitative choice of fade rates for the direct and refracted paths is, unfortunately, not as clearly supported in the literature. To assist, the following reasoning was applied: (1) The range of mean fade rates of the direct component can be obtained from the statistics of "shallow fades," i.e., fades of less than 20 dB below the unfaded value. An initial survey of LOS propagation literature indicates that a range of .01 Hz-.1 Hz is reasonable (15). (2) The range of mean fade rates of the refracted component cannot be similarly deduced since the volume of fade rate data taken exclusively during deep fading (greater than 20 dB below the unfaded value) is not sufficiently large. Thus, a resort to theory is necessary. Since the refracted component is propagated along a "tropospheric" route, fade rates associated with tropospheric scatter propagation at the frequency of operation are assumed for the refracted component. Based on accepted estimation relationships for troposcatter fade rates (16), a range of mean fade rates of .1-1.0 Hz will be assumed in the model to describe the time selectivity of the refracted component.

Since the fading envelope correlations obtained on DCS LOS space diversity links are high for practical antenna spacings, it is necessary to incorporate the capability for correlated direct path fading by using partially correlated noise sources. Fading of the refracted component(s) will be assumed as effectively uncorrelated, based on established troposcatter space diversity propagation. A range of direct path correlation coefficients of .5 to .95 will be used.

The power and delay relationships of the direct and refracted components are complex and quite topographically and meteorologically dependent. To accommodate most channels of interest, the following channel parameters will be made variable within the indicated ranges:

- Number of active taps and relative amplitudes (up to 10 taps with a 30 dB relative power differential).

- Intertap spacing from 0.1 bit to 1.0 bit inclusive.



NOTE:

G_1^* - Complex Tap Weight for Direct Path

G_2^{i*} - Complex Tap Weight for ith component of refracted path

- *Attenuator to vary direct/refracted path power ratio*

Figure 15. LOS Hybrid Computer Simulation (Single Diversity Channel)

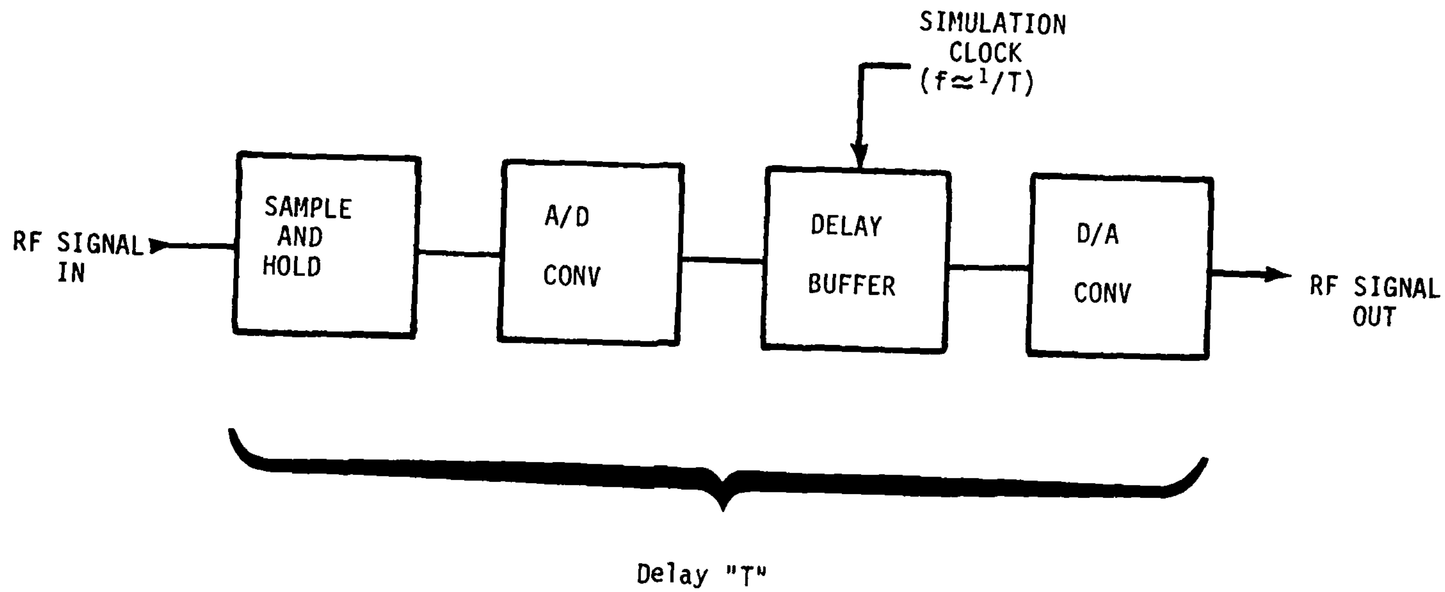


Figure 16. LOS Path Delay Module

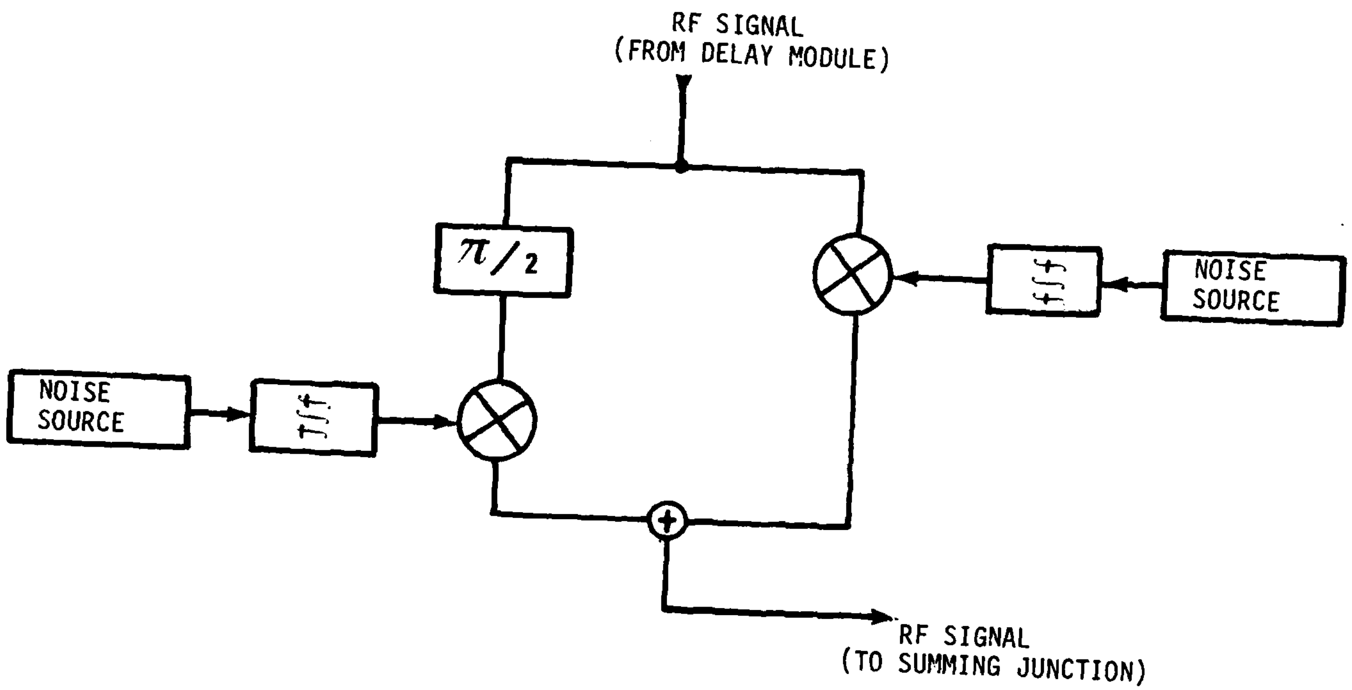


Figure 17. Component Fading Module

VI. PROGRAM SUMMARY

1. STUDY OBJECTIVES

The objectives of the study effort under which this report is written are:

a. To assess the impact of frequency selective fading of the microwave Line-Of-Sight (LOS) propagation channel on the allocation of system performance and DCS LOS link design as derived in DCEC TR 12-76, DCS Digital Transmission System Performance (3).

b. To evaluate whether adaptive equalization is necessary to obtain reasonable performance on digital LOS links. This aspect of the effort is envisioned to have most significance in system performance specifications for wideband digital LOS systems such as the 90 Mb/s Washington Area Wideband System (WAWS) and to a lesser extent in specification of the more nominal 13-26 Mb/s DCS LOS systems such as the Digital European Backbone (DEB).

2. STUDY APPROACH

The approach to be used in this assessment will employ hybrid computer simulation techniques and link propagation testing to provide both parametric data on modulation and diversity combiner performance and statistical data on the rate of occurrence of frequency selective efforts and associated correlations. Additionally, from a study of available literature, it is known that a number of organizations have a similar interest in assessing frequency selective fading on LOS microwave links. On this basis, DCEC plans to solicit these organizations for interest in exchanging information and test data. Specific efforts are planned in the following areas:

a. Model Development and Media Simulation - Development of enhanced LOS media models which can explicitly account for the effects of antenna size, antenna orientation, link topography and climate type. Hybrid computer simulation of the selective fading LOS channel to enable subsequent performance evaluation of the AN/FRC-( )( ) QPR radio.

b. Digital Performance Analysis - Hybrid Computer Models developed from the AN/FRC-( )( ) QPR radio design will be evaluated using the hybrid computer channel simulation to parametrically evaluate the AN/FRC-( )( ) design over a range of LOS paths inclusive of DoD applications.

c. Diversity Combiner Analysis - The dual diversity combiner used in the AN/FRC-( )( ) radio is a selective combiner and uses the diversity combiner control algorithm derived by J. Osterholz (4). Since the key to mitigating time dispersive multipath fading centers about the use of diversity and the diversity combiner control algorithm, the AN/FRC-( )( ) dual diversity combiner will be modeled and evaluated under simulated frequency selective fading conditions. The results of this task will provide the basis by which modification of the link design methods and system design criteria contained in DCEC TR 12-76 (3) can be initiated, if shown necessary.

d. A one-day seminar at DCEC is planned for the purpose of exchanging information on the effects of frequency selective fading on digital radio communications. Leading authorities from government and industry will be invited.

e. Operational Link Testing - ITS is currently collecting propagation data on selected DEB I links under Air Force sponsorship. This effort is being expanded to measure and analyze receiver spectra to determine the degree of frequency selective fading on the longer links in DEB I. The display from a spectrum analysis will be recorded along with other parameters including received signal level and multiplex reframes. Analysis of these data will then establish preliminary estimates of frequency selectivity effects on partial response modulation at data rates of 12.6 Mb/s.

f. Experimental Link Testing - Detailed Propagation testing over one or more wideband (20-40 MHz radiated bandwidth) Washington Area LOS microwave links will be performed. Link testing will assist in determining the following:

(1) The frequency of occurrence and duration statistics of frequency selective fading (e.g., are all deep LOS fades frequency selective?).

(2) The existence of correlative effects which can be exploited to minimize the occurrence of frequency selective fading (e.g., is increased frequency selectivity always associated with a direct path fade?).

(3) The extent that frequency selectivity is observed over the bandwidths of interest (14 MHz, 20 MHz, and 40 MHz). Measurement and statistical characterization of RF amplitude and delay characteristics.

(4) Data which, together with existent Bell Telephone Laboratories (BTL) and Bell Northern Research (BNR) results, will increase confidence that the model developed earlier in this effort provides a reasonable estimate of the effects of frequency selective fading on wideband digital LOS communications.

Additionally, some digital performance testing would also be highly desirable. Unfortunately, because of the difficulty of performing simultaneous propagation and digital performance testing, the ideally desired relationship between inband propagation and digital performance is not available. However, by appropriately interleaving digital performance tests with propagation measurements made during link fading periods, it is anticipated that at least the first order relationships between inband channel fluctuations and digital performance can be determined. The main thrust of the digital performance tests is to determine whether the empirical constants used in the LOS transmission system design methods derived in DCEC 12-76 remain valid in intersymbol interference limited environments such as that reported by BTL on 45-90 Mb/s microwave LOS links, or on lower data rate DCS LOS links of unusually long distance.

g. Laboratory Test of DRAMA Radio - During first article testing of the DRAMA system, a laboratory test is planned (see ref 17) to determine the effect of multipath fading on the DRAMA radio. A two-ray model will be used, with the secondary ray attenuated and delayed to simulate multipath conditions. Performance of the DRAMA radio will be characterized under these conditions.

h. Adaptive Equalizer Applique (AEA) - The use of an adaptive equalizer taken from the hybrid computer model of the digital troposcatter Adaptive Decision Feedback Equalizer (ADFE) will be evaluated as an applique to the DRAMA radio. Specific areas to be addressed are:

(1) Number and spacing of equalizer taps.

(2) Decision vs reference directed equalizer adaptation.

(3) Equalizer convergence algorithm(s).

3. REPORTS

The following reports will be generated during the course of this effort:

Report No. 1 - Channel Modeling and Hybrid Computer Simulation. This report will summarize the study approach and describe the theoretical basis of the hybrid computer modeling effort as it relates to simulating the selectivity fading LOS microwave channel and the AN/FRC-( )( ) Radio.

Report No. 2 - Seminar on Frequency Selective Fading and Its Effects on Digital Radio. This report will present results of the government/industry seminar planned at DCEC in the form of papers or slides presented at the seminar.

Report No. 3 - DEB I Operational Link Performance Characterization. This final report will describe results, analysis, and conclusions from DEB I link testing and will provide recommendations for a more comprehensive test with an experimental digital link.

Report No. 4 - Laboratory Test of DRAMA Radio. This report will present results from lab tests of the DRAMA radio operation over a simulated multipath environment.

Report No. 5 - Digital Radio Performance Evaluation. This report will present the results of the hybrid computer performance simulations of the AN/FRC-( )( ) digital radio using a selection diversity combiner. This evaluation will be accomplished using the frequency selective fading channel model developed as part of this effort and described in Report No. 1.

Report No. 6 - Experimental Link Performance Characterization. This report will present the results and a summary of the pertinent data from the first phase of the experimental link testing.

Report No. 7 - Adaptive Equalizer Applique Evaluation. Based on the available link performance data and the hybrid computer performance models of the AN/FRC-( )( ) radio, an evaluation will be made of the need for an adaptive equalizer applique. This evaluation will be based on an estimate of the percentage of DCS links likely to require equalization (based on the requirements of DCEC TR 12-76) and will result in a recommendation as to the practicality of implementing an adaptive equalizer applique for use with the AN/FRC-( )( ) radio on DCS LOS links. Additionally, the current Washington Area Wideband System performance specification will be reviewed and a recommendation will be made as to its continued practicality (with and without adaptive equalization) and, if required, revised system performance specification will be recommended which can be achieved in a cost effective manner.

4. SCHEDULE

The milestone chart shown in Figure A-1 details the planned schedule for this effort.

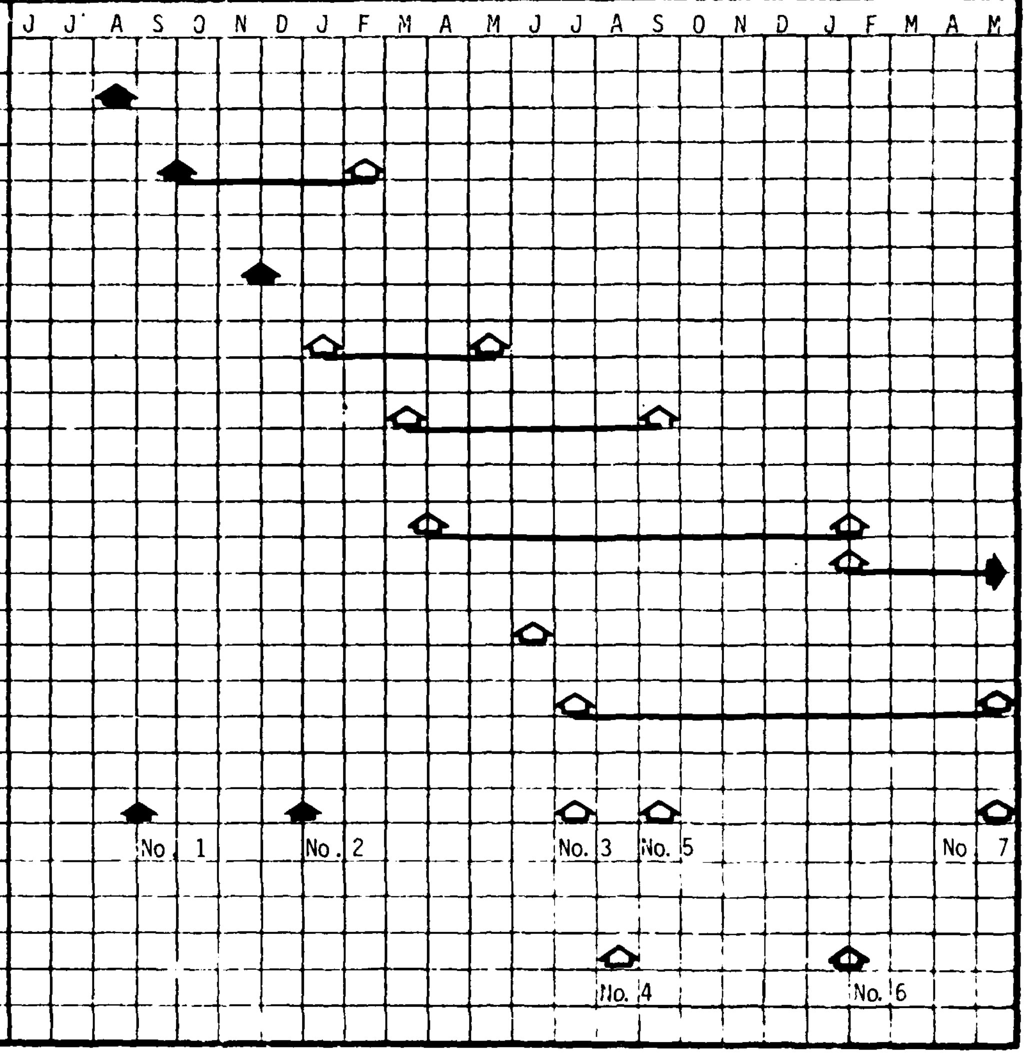
PAGE __ OF __

DEFENSE COMMUNICATIONS AGENCY MILESTONE CHART

SCHEDULE NO. ____

TITLE	CLASSIFICATION	AS OF DATE
Figure A-1 Assessment of Frequency Selective Fading on LOS Links	UNCLASSIFIED	June 1979

ITEM NO.	MAJOR MILESTONES
1.	Channel Modeling
2.	AN/FRC-( )( ) Simulation Verification
3.	Seminar
4.	DEB Operational Test
5.	Digital Radio Performance
6.	Experimental Test
	Phase A
	Phase B
7.	Laboratory Test of DRAMA Radio
8.	Adaptive Equalizer Evaluation
	Reports



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PREVIOUS EDITIONS OF THIS FORM ARE OBSOLETE

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LIST OF ACRONYMS

ADFE - Adaptive Decision Feedback Equalizer
AEA - Adaptive Equalizer Applique
AGC - Automatic Gain Control
BCI - Bit Count Integrity
BER - Bit Error Rate
BNR - Bell Northern Research
BTL - Bell Telephone Laboratories
DPS - Delay Power Spectrum
DPSK - Differential Phase Shift Keying
DRAMA - Digital Radio and Multiplex Acquisition
IMD - Intermodulation Distortion
ISI - Intersymbol Interference
LOS - Line of Sight
OTM - Offset Threshold Monitoring
PRDS - Psuedo-Random Data Stream
PRF - Partial Response Filter
PSK - Phase Shift Keying
QPR - Quadrature Partial Response
QPSK - Quadrature Phase Shift Keying
RSL - Received Signal Level

APPENDIX A

MULTIPATH DELAY POWER SPREAD

COMPUTER PROGRAM

```
      IMPLICIT REAL*8 (A-I,K,M,O-Y)
      IMPLICIT INTEGER*4 (J,L,N,Z)
      DIMENSION S(101),D(101),A(5)
      Z=41
      M=5.0
150   WRITE(6,100)
100   FORMAT(' ','ENTER PATH LENGTH IN MILE
      READ(5,200)D1
      WRITE(6,200)D1
200   FORMAT(F10.3)
      WRITE(6,210)
210   FORMAT(' IS THIS A SMOOTH EARTH PATH?  1=YES, 0=NO')
      READ(5,3000)LANS
      IF(LANS.EQ.1)GO TO 240
      WRITE(6,230)
230   FORMAT(' ENTER HORIZON ANGLES IN DEGREES ONE AT A TIME')
      READ(5,200)ALF
      READ(5,200)BET
      WRITE(6,200)ALF
      WRITE(6,200)BET
      ALF=.00872*ALF
      BET=.00872*BET
240   WRITE(6,300)
300   FORMAT(' ','ENTER EFFECTIVE EARTH  (K)')
      READ(5,200)K1
      WRITE(6,200)K1
      D0=(D1/3963.)*(D1/3963.)/(8.*K1*K1)
      WRITE(6,400)
400   FORMAT(' ENTER THE ANTENNA BEAMWIDTHS IN DEGREES ONE AT A T
      READ(5,200)B1A
      READ(5,200)B1B
      WRITE(6,200)B1A
      WRITE(6,200)B1B
      B1A=.00872*B1A
      B1B=.00872*B1B
      WRITE(6,500)
500   FORMAT(' ','ENTER NUMBER OF POINTS DESIRED AT 50 NS SPACING
      READ(5,600) N1
      WRITE(6,600)N1
600   FORMAT(I2)
      S1=.00937/D1
      C1=D1/(K1*7926)
      B2A=.35/(B1A*B1A)
      B2B=.35/(B1B*B1B)
      IF(LANS.EQ.0)GO TO 270
      ALF=C1
      BET=C1
270   M1=M/2.
      M2=1.+M/2.
```

```
      S4=0.
      DO 10 J=1,N1
      D3=FLOAT(J)*S1+D0
      U2=DSQRT(D3/D0)
      U1=DSQRT(D0/D3)
      D4=DSQRT(2*D3)
      DO 20 JI=1,Z
      ZM1=Z-1
      L=JI-1
      S(JI)=U1+FLOAT(L)*(U2-U1)/FLOAT(ZM1)
      X1=S(JI)
C     WRITE(6,101) J,JI,G1,G2,X1,D4,C1
101   FORMAT(' ',2I3,5F20.5)
      G1=DEXP(-B2A*((X1*D4-ALF)**2))
      G2=DEXP(-B2B*((-BET+D4/X1)**2))
      X3=X1*((X1+1./X1)**M1)
      D6=1./(D3**M2)
      Q(JI)=D6*G1*G2/X3
20    CONTINUE
      JI=1
      JIM1=JI-1
      AA=0.
640   JI1=JI+1
      JI2=JI+2
      IF(JI.GE.Z)GO TO 780
      H=S(JI1)-S(JI)
      IF(DABS((S(JI2)-S(JI1))-H).GT.1.0E-8) GO TO 720
      AA=AA+H*(Q(JI)+4*Q(JI1)+Q(JI2))
      JI=JI2
      GO TO 640
720   IF(DABS(H-(S(JI)-S(JIM1))).GT.1.0E-8) GO TO 760
      AA=AA+H*(5*Q(JI1)+8*Q(JI)-Q(JIM1))*.25
      JI=JI1
      GO TO 640
760   WRITE(6,1100) S(JI),S(JI1),S(JI2)
1100  FORMAT(' ','IMPOSSIBLE TO INTEGRATE X VALUES: ',3(1X,F15.6))
      STOP
780   AA=AA/3.0
      A(J)=AA
      S4=S4+AA
10    CONTINUE
      WRITE(6,700)
700   FORMAT(' ','DELAY USEC',15X,' POWER',20X,'AMPLITUDE')
      DO 30 J=1,N1
      FIRST=FLOAT(J)*.05
      SECOND=A(J)/S4
      THIRD=DSQRT(A(J)/S4)
30    WRITE(6,800)FIRST,SECOND,THIRD
800   FORMAT(' ',3(2X,E20.6))
      WRITE(6,2000)
2000  FORMAT(' DO YOU WANT TO DO ANOTHER PATH? 1=YES, 0=NO')
      READ(5,3000)JANS
3000  FORMAT(I1)
      IF(JANS.EQ.1) GO TO 150
      STOP
      END
```

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